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1966
BARTOCCI, J.

CASCADE TESTS OF THE BLADING OF A
HIGH-DEFLECTION, SINGLE-STAGE, AXIAL-FLOW
IMPULSE TURBINE AND COMPARISON OF RESULTS
WITH ACTUAL PERFORMANCE DATA

JOHN EUGENE BARTOCCI

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CASCADE TESTS OF THE BLADING OF A HIGH-DEFLECTION,
SINGLE-STAGE, AXIAL-FLOW IMPULSE TURBINE
AND COMPARISON OF RESULTS WITH
ACTUAL PERFORMANCE DATA

by

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Submitted in partial fulfillment
for the degree of

AERONAUTICAL ENGINEER

from the

UNITED STATES NAVAL POSTGRADUATE SCHOOL
May 1966

NPS ARCHIVE
1966

BARTOCCI, J.

B24224
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ABSTRACT

Cascade tests were performed on models of the stator (nozzles) and rotor blade rows of a high deflection, single-stage, axial-flow impulse turbine. The tests were performed at the Rectilinear Cascade Test Facility of the Propulsion Laboratories, United States Naval Postgraduate School. The results of these tests were compared with the performance data of the actual turbine. The comparison showed that profile and mixing losses, though not negligible, constitute only a small percentage of the overall rotor loss. Also, the inlet flow angle at which the minimum loss occurred for the Cascade flow was significantly different from the inlet flow angle at which minimum actual rotor loss occurred.

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TABLE OF SYMBOLS

a	speed of sound, ft./sec.
c	chord of test blade, ft.
C_D	drag coefficient, dimensionless
C_L	lift coefficient, dimensionless
c_p	specific heat at constant pressure, BTU/lbm $^{\circ}\text{R}$.
D	drag force, lb./ft.
\dot{m}	mass flow rate, lb. sec./ft.
g	gravitational constant, ft./sec. ²
h	test blade height, ft.
\hat{i}	unit vector in tangential direction, dimensionless
\hat{j}	unit vector in axial direction, dimensionless
J	conversion factor, ft. lb./BTU
L	lift force, lb./ft.
M	Mach number, dimensionless
\hat{n}	unit vector normal to control/surface, dimensionless
P_s	absolute static pressure
P_t	absolute total pressure, lb./ft. ²
q	dynamic pressure, lb./ft. ²
R	gas constant, ft./ $^{\circ}\text{R}$
\vec{R}	force exerted by fluid on test blade, lb./ft.
s	blade spacing, ft.
T	temperature, $^{\circ}\text{R}$ or $^{\circ}\text{F}$
V	fluid velocity, ft./sec.
W	flow velocity relative to rotor blades, ft./sec.

x distance in tangential direction, ft.
 y distance along blade height, ft.
 z distance across blade channel at the discharge, ft.
 α gas flow angle, deg.
 β angle between \hat{i} and \vec{V} , deg.
 γ ratio of specific heats, dimensionless
 ζ loss coefficient, dimensionless
 θ (subscripted) flow angle between \hat{j} and \vec{V} , deg.
 θ (non-subscripted) angle between \hat{i} and \vec{R} , deg.
 ρ mass density, lb. sec.²/ft.⁴
 σ solidity, c/s, dimensionless
 ϕ stagger angle, deg.
 ψ velocity coefficient, dimensionless
 ξ area restriction factor, dimensionless
 ΔX total distance traversed, ft.
 Δx distance between measuring points, ft.
 μ viscosity, lb./ft. - sec.

Subscripts

atm atmospheric
 i tangential direction
 j axial direction
 p plenum
 R rotor
 s static

- t total
- o station o, far ahead of the cascade
- 1 station 1, measuring plane ahead of cascade
- 2 station 2, measuring plane aft of cascade
- 3 station 3, far aft of cascade
- ∞ vectorial mean of conditions at stations o and 3

1. Introduction

The need for light-weight, efficient gas turbines that are capable of developing large amounts of power has caused much interest in the flow through low-reaction stages having gas deflections in excess of 110° . Very little performance data on such stages are available and the quest for an efficient design in many instances has become an expensive trial and error process.

The cascade testing of blade rows, performed in conjunction with tests on actual turbines that have the same blade row geometry, is a logical way to learn more about the phenomena involved in the flow through these turbine stages. This work compares the results of cascade tests conducted at the Rectilinear Cascade Test Facility with the results of tests performed on the corresponding actual turbine stage. Two cascade tests of the stator or nozzle blade row were made. Both tests were performed at near design inlet flow angle. Five cascade tests of the rotor blade row were made, each at a different flow angle. The actual turbine performance data are obtained from tests with the Transonic Turbine Test Rig. [9]

A method that would predict the losses of high deflection turbine stages with accuracy would indeed be of value to the turbine designer. The purpose of the comparison of results,

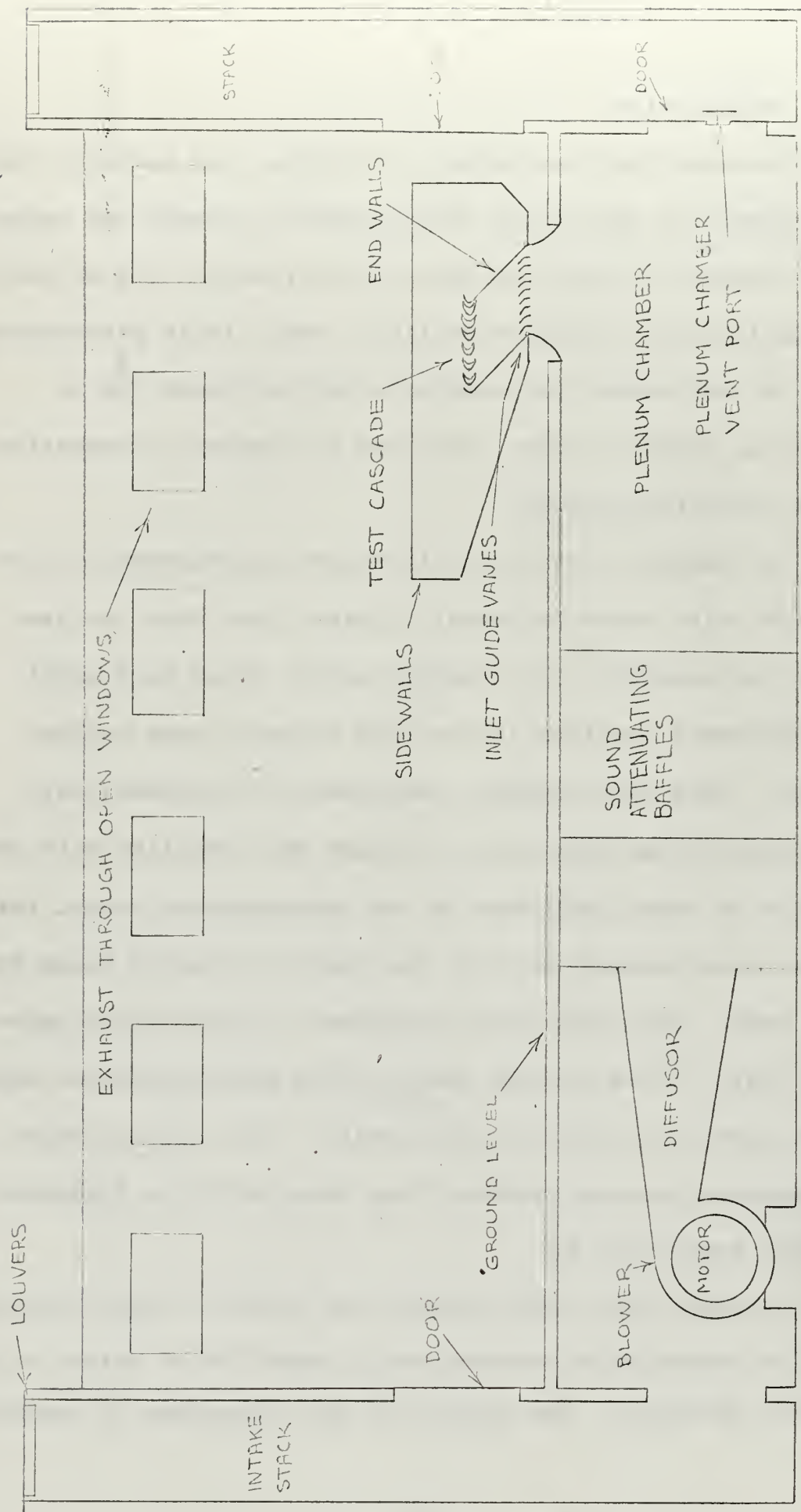


FIGURE 1
SCHEMATIC OF THE CASCADE TEST FACILITY

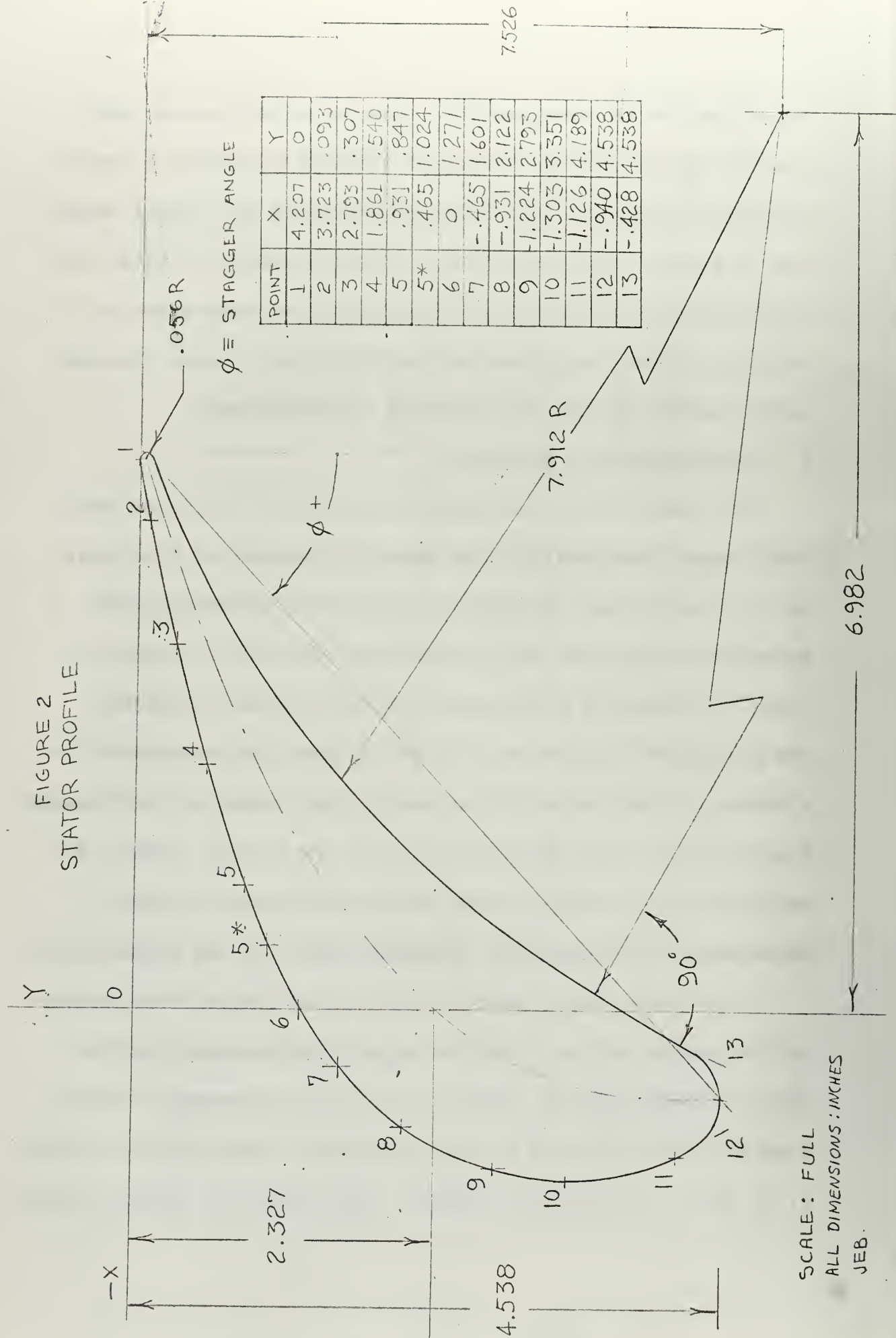
therefore, is to seek possible ways in which cascade test results may be related to actual turbine performance and to determine a basis on which recommendations for future study may be made. It is hoped that future research in this area will eventually lead to the formulation of some means of accurate turbine performance prediction and a more thorough understanding of the flow through turbomachines.

2. Description of Apparatus

The Rectilinear Cascade Test Facility is an open-cycle wind tunnel designed for the specific purpose of flow testing of rectilinear cascades of axial-flow turbomachines. A schematic diagram of the Cascade Test Facility is shown in Fig. 1. A detailed description of the Cascade Laboratory and associated equipment is given by Rose and Guttormson in a thesis on the installation and initial tests of the Cascade Test Facility. [10] Modifications to the plenum chamber are described in a United States Naval Postgraduate School, Department of Aeronautics, Technical Note by the writer. [6]

The blade shapes used in this investigation were models of the stator and rotor of an actual single-stage turbine which is being tested concurrently in the Transonic Turbine Test Rig, also located at the Propulsion Laboratories of the U. S. Naval Postgraduate School. The stator or nozzle profile

FIGURE 2
STATOR PROFILE



is shown in Fig. 2. The stators are of the converging nozzle type with a chord of 6.66 inches, a blade spacing of four inches and a stagger angle of 48° . Stagger angle is defined as shown in Fig. 2.

The rotor profile geometry is shown in Fig. 3. Of note is the fact that the shape geometry is composed solely of straight lines and circular arcs, that the leading and trailing edges are not rounded, and that the blade shape is designed for large flow deflection, namely 132° . The rotor blade models have a chord of 6.657 inches and a blade spacing of four inches. The stagger angle is -4.5° .

The arrangement of the cascade test section for the stator blading is shown schematically in Fig. 4. Straight inlet guide vanes were used and the end walls were positioned vertically so that the flow would come straight up to the stator profiles. The stator cascade had a total of 15 blades. There were 30 inlet guide vanes spaced two inches apart. End walls were not installed aft of the blade models, however, metal fairings were arranged between the lower end walls and the adjacent blade models. Fig. 5 is a view of the stator cascade with the removable side wall installed. Rubber gasket material was cut to the shape of the profile and cemented to the end of the model. This was done to prevent the passage of air between the model and the removable side wall.

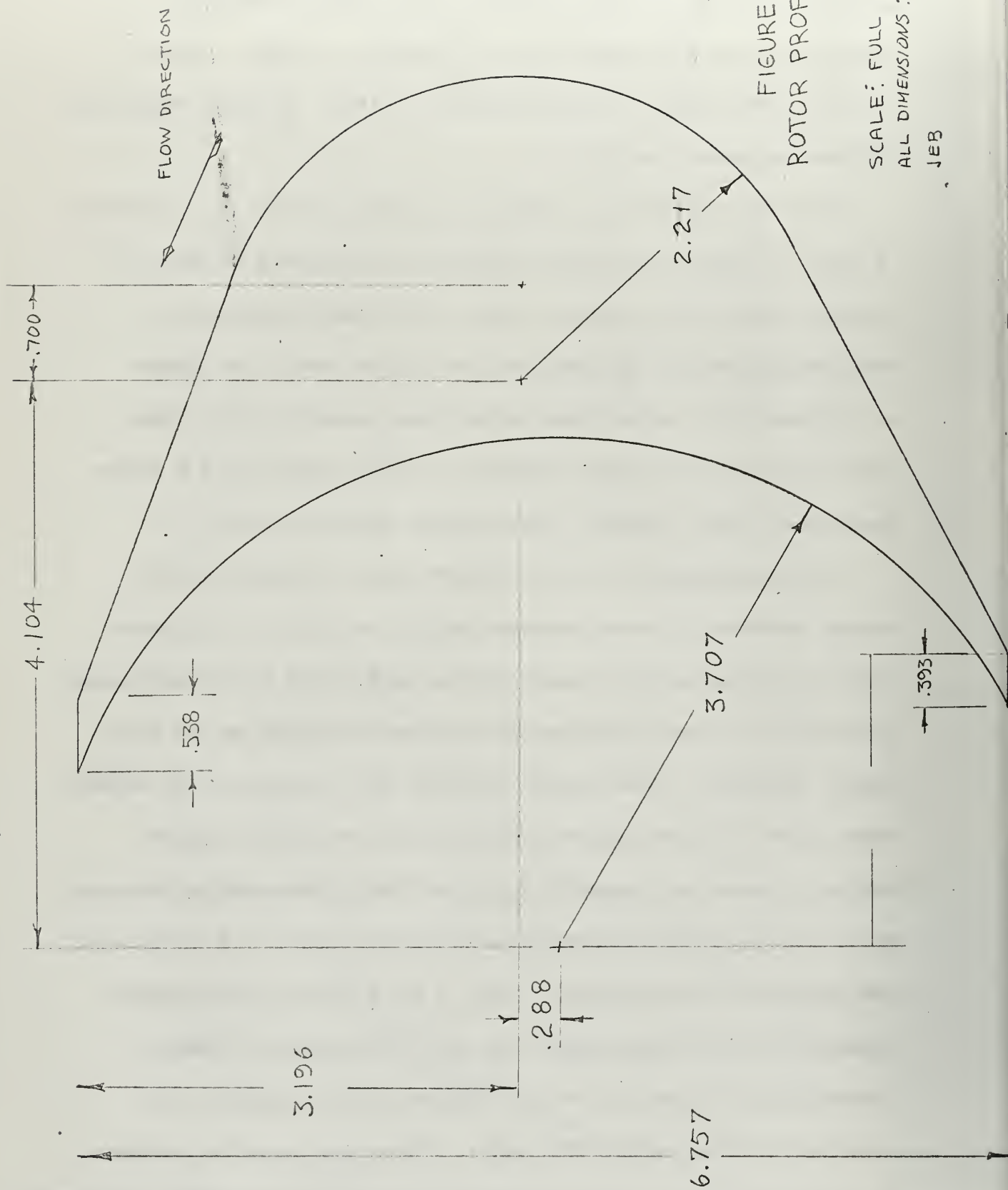


FIGURE 3
ROTOR PROFILE

SCALE: FULL
ALL DIMENSIONS: INCHES
JEB

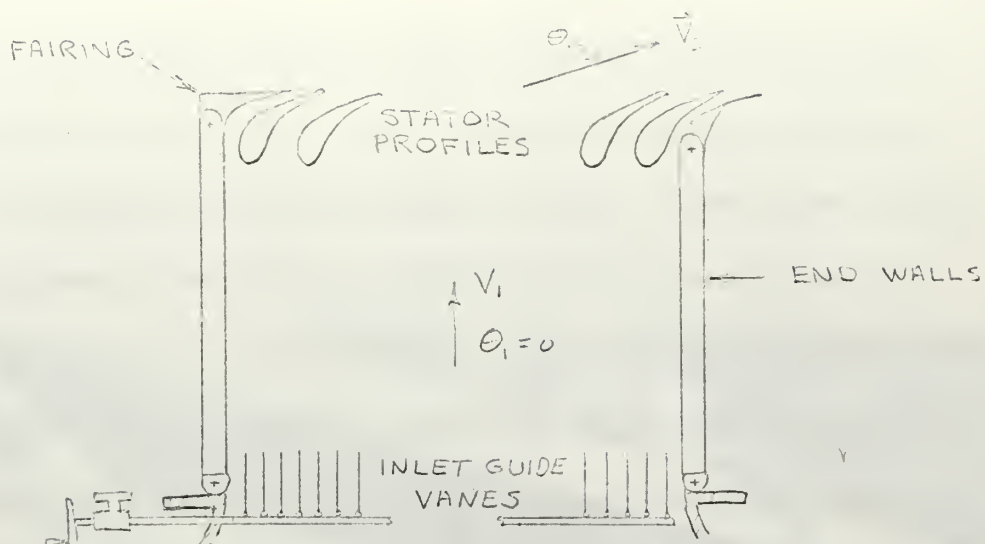


FIGURE 4
TEST SECTION CONFIGURATION : STATOR CASCADE

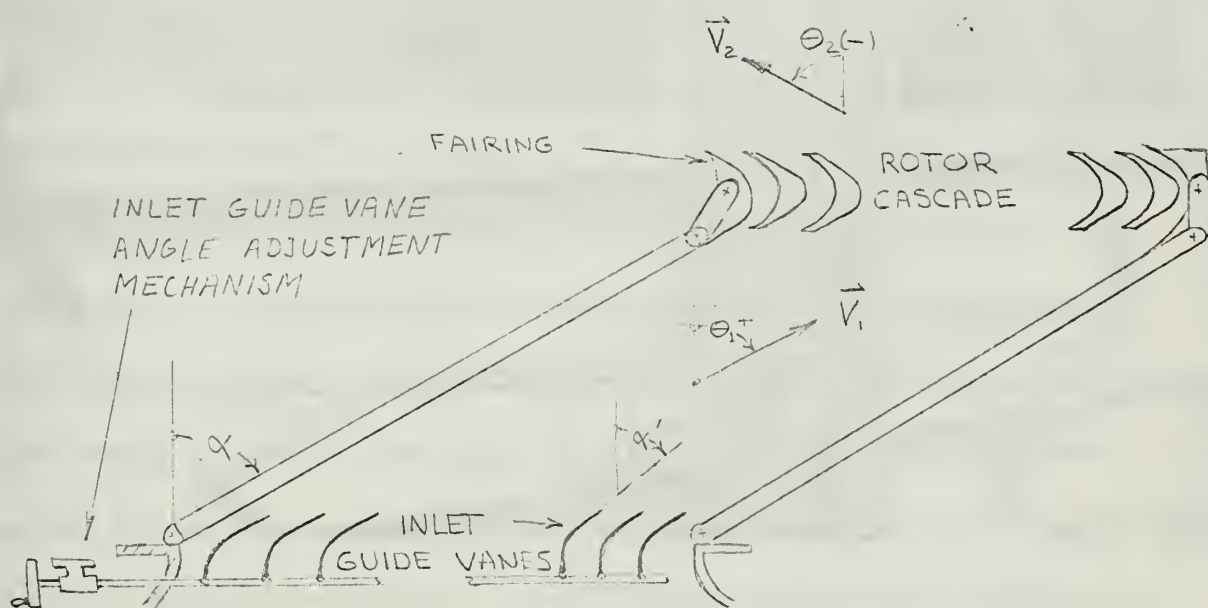


FIGURE 6
TEST SECTION CONFIGURATION : ROTOR CASCADE

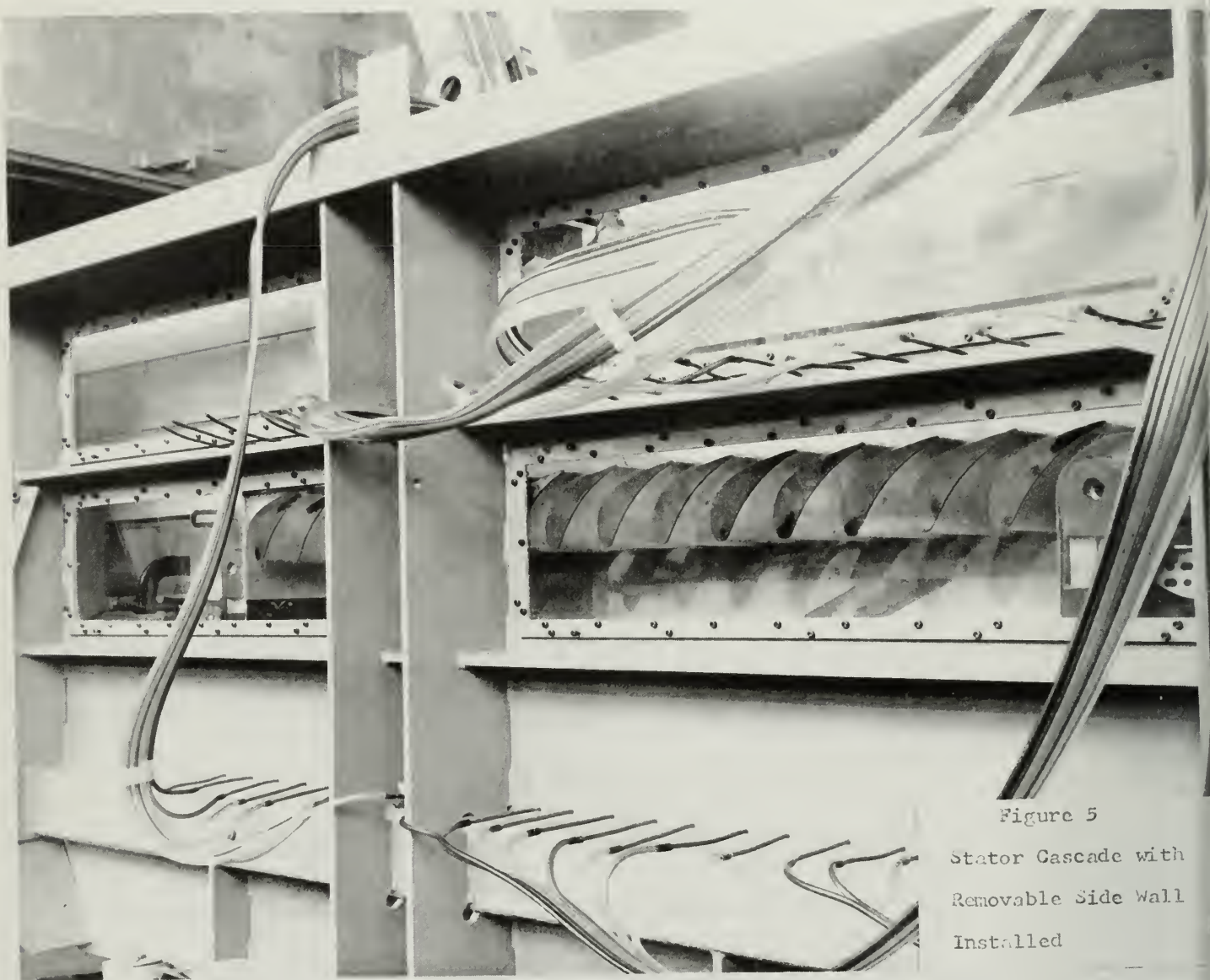


Figure 5
Stator Cascade with
Removable Side Wall
Installed

The arrangement for the rotor cascade tests is shown schematically in Fig. 6. Inlet guide vanes with 60 degree nominal deflection were installed. Inlet guide vane spacing was two inches. The total number of guide vanes was 30, and there were 15 blades in the rotor cascade. The end walls were positioned parallel to each other. Different inlet flow angles Θ_1 were obtained by changing the angle α of the end walls and by adjusting the angle α' of the inlet guide vanes. The inlet guide vanes are mechanically linked so that angular positioning of all the inlet guide vanes can be accomplished simultaneously.

3. Instrumentation

Pressure and flow angle measurements of the flow in the cascade test section were made by using two United Sensor and Control Corporation YC-120 probes. These probes are designed to measure total pressure, static pressure and yaw angle. The wedge-type probe head has one total pressure sensing port (P1), and two static pressure sensing ports (P2 and P3). When the probe is inserted into a flow, the total pressure sensing port is oriented into the flow direction when P2 and P3 are equal. The YC-120 probes were mounted in the upper and lower carriages in the manner described in [10]. Pressures which were measured directly were total pressure (P_t) and the difference between total and static pressure (q).

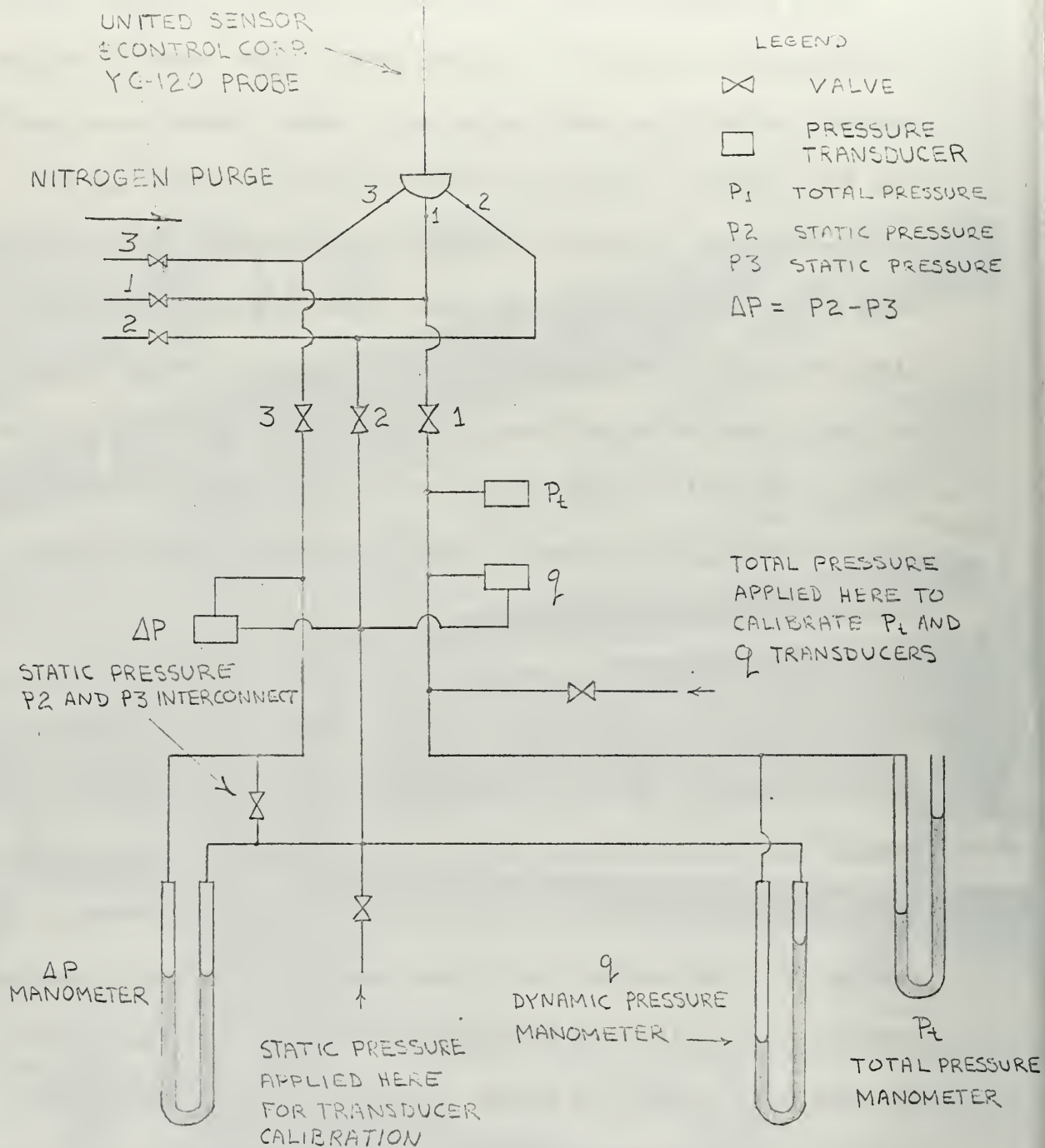


FIGURE 7

INSTRUMENTATION SYSTEM
SCHEMATIC . TYPICAL FOR BOTH UPPER
AND LOWER TRAVERSES

The probes are connected to an automatic data logging system which utilizes electric pressure transducers, and to a back-up system with water manometers as pressure gages. The system has provisions for calibrating the automatic data logging system by applying pressures to the transducers which can be read on the water manometers. A protractor was installed on the probe carriage housing so that flow angle calibration of the automatic data logging system could be accomplished, and that flow angle could be read directly. A schematic diagram of the system is given in Fig. 7. The system shown is typical for both the upper and lower traverse. The system has provisions for blowing out the probes with Nitrogen to insure that foreign particles do not clog their capillary tubings. A set of three valves is used to isolate the pressure transducers and water manometers from the Nitrogen system that operates at relatively high pressures.

Static pressure taps located in the test section side walls were used to monitor the static pressure distributions in the test section. There are two rows of taps in each side wall. The rows are parallel to the cascade axis and the taps are spaced three inches apart. The lower rows of static taps are located four inches ahead of the lower traverse, and the upper rows of static taps are located aft of the blade models but four and one quarter inches ahead of the



Figure 8
Vernier Probe Holder
Position with Stator
Cascade

upper traverse. The static pressure taps are connected to three 97-inch water manometer banks.

A pressure tap located in the plenum chamber and connected to a 40-inch manometer is used to measure the plenum pressure. The fluid used in this manometer has a specific gravity of 1.75. A thermometer probe located in the plenum was used to determine the plenum temperature. Atmospheric pressure was read from a standard mercury column barometer.

In order to investigate the flow within a blade channel, a pitot-static probe was placed in a vernier probe holder. The assembly was then mounted in the cascade test section between the side walls as shown in Fig. 8. The probe holder assembly was positioned so that the probe head could be moved along the exit plane of a blade channel. Fig. 9 and Fig. 10 show the probe positioning for the stator and rotor blade modes respectively. The pitot-static probe head used had a diameter of 0.065 inches. A total pressure probe was also made to fit the vernier probe holder. This probe had a thickness of 0.019 inches at the tip. The vernier probe holder allowed the probe to be moved in increments of 0.01 inch. Total pressure and dynamic pressure were measured using two 40-inch water manometers.

Due to malfunctions in the automatic data logging system, the back-up manual system was used to conduct this investigation.

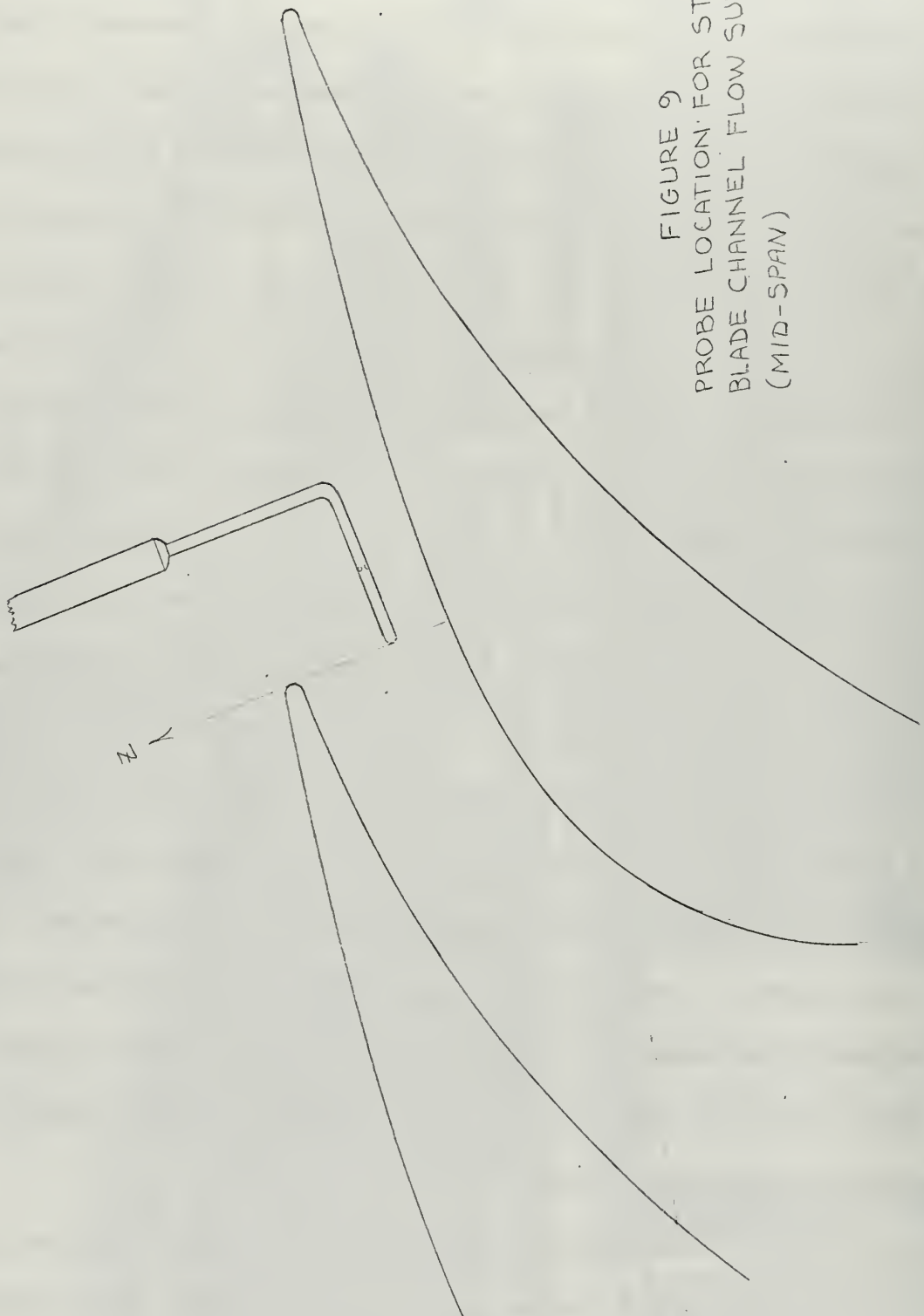


FIGURE 9
PROBE LOCATION FOR STATOR
BLADE CHANNEL FLOW SURVEY
(MID-SPAN)

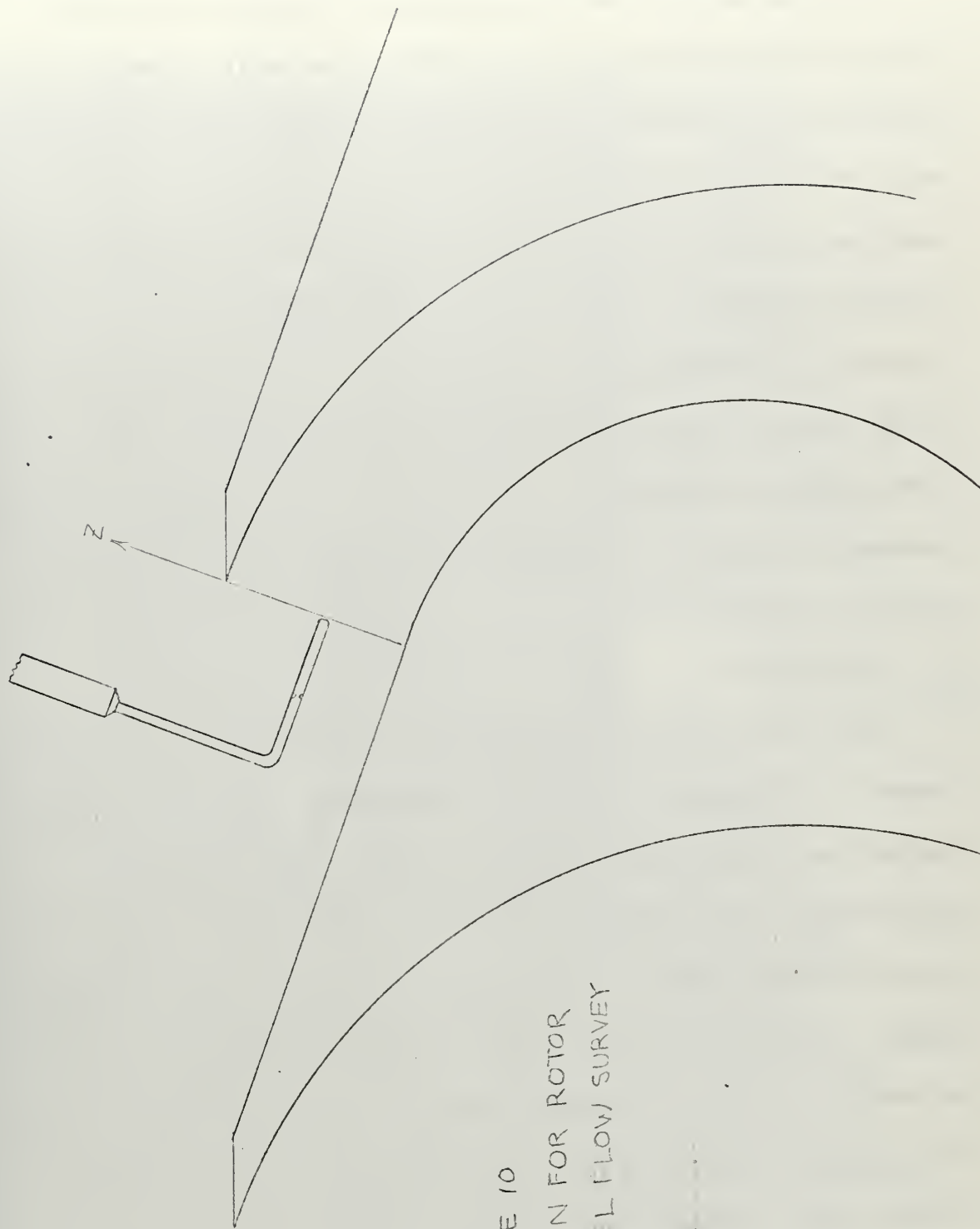


FIGURE 10
PROBE LOCATION FOR ROTOR
BLADE CHANNEL FLOW SURVEY
(MID-SPAN)

All manometers were graduated in tenths of an inch, and the protractors associated with flow angle readings were graduated in degrees. The pressure measurements could be read accurately to within one-half a graduation. The readings within half a graduation are estimates based on the position of the meniscus at the time of the observation. For instance, a reading of $q=25.28$ inches of water means $25.30 < q < 25.30$ but that the pressure reading is closer to 25.30. Flow angle measurement is considered to be accurate to within one-half a degree. A recorded value of $\theta = 62.3^\circ$ means $62^\circ.0 < \theta < 62^\circ.5$.

4. Procedure

The test section was first set up for the stator model tests in the manner previously described. After the blade models, entrance guide vanes, end walls and fairings were positioned, the removable side wall was installed, and the static pressure taps were connected to the 97-inch manometer banks. During the preliminary runs, with the motor running at medium speed, the blower started to surge as the flow rate through the test section was increased by opening the blower inlet vanes. Since the stator blades turn the flow by about 75° , the flow area at the discharge of the stator blades is only about one-fourth of the flow area ahead of them. The pressure required to discharge the whole flow rate of the

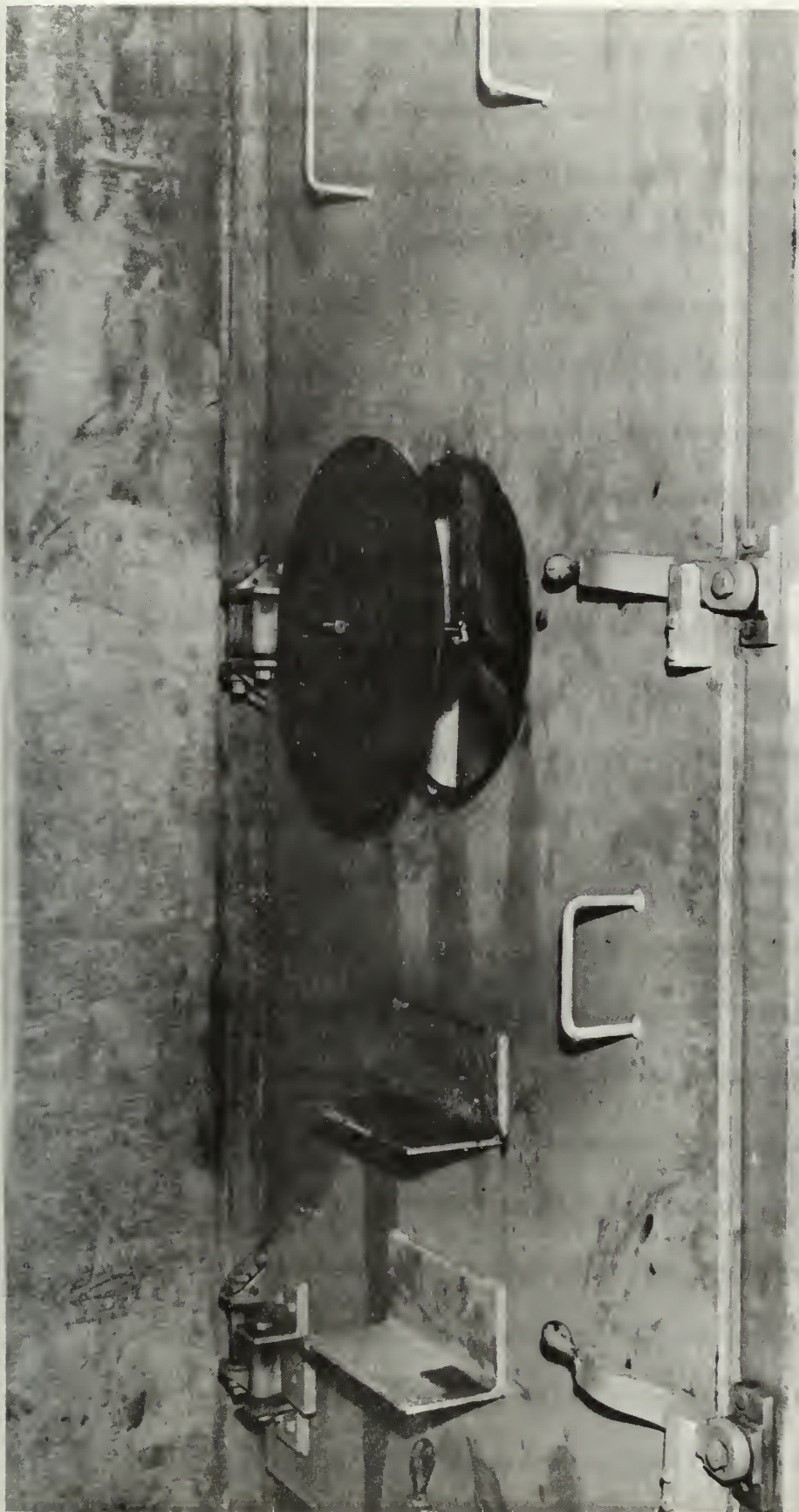


Figure 11
Plenum Chamber Vent Port

blower through the cascade was higher than that which could be produced by the blower without surging. It was therefore necessary to vent part of the flow delivered by the blower directly from the plenum chamber to the atmosphere. This was accomplished by cutting a hole of 16 inches in diameter in each of the two steel doors that give access to the plenum chamber. Cover plates were manufactured for these holes to adjust the effective by-pass flow area. With these plates, one of which is shown in Fig. 11, it was possible to operate the blower at the desired plenum pressure without surging. The location of these vent ports is shown in Fig. 1. It can be seen that the by-pass flow is discharged to the atmosphere through the stack adjacent to the plenum chamber.

Prior to the start of data acquisition, the lower probe was positioned six inches beyond the geometric center of the test section along the cascade axis. The middle probe position along the upper cascade axis was determined by the intersection of a line projected along the design discharge angle from the trailing edge of the center blade and the upper traverse. The starting position for the upper probe was six inches to the same side of center as the lower probe. After the pressure lines of the instrumentation were checked for possible air leaks, the zero flow angle position of the YC-120 probes was set, and the manometers were set at zero.

The blower was then started and the desired plenum pressure set. It was found that an initial decrease in plenum pressure occurred just after start. For instance, with the blower set at medium speed, blower inlet vanes open, the initial plenum pressure was approximately 26.5 inches of H_2O . Within the first half hour of blower operation, the plenum pressure would generally drop 0.8 to 1.2 inches of H_2O and then stabilize.

Once a test run was initiated, the probes were moved along the cascade axis (in the x direction) by manually turning the traverse carriage drive screw instead of using the electric drive. A hand crank was attached to the gearing of the electric motor that moves the carriage along the cascade axis. One turn of the hand crank moved the carriage (and consequently the probe) 0.01 inch. This method of incremental movement of the probe was used since exact positioning of the probe by means of the electric drive motor controlled by the toggle switch located on the automatic data logging system console was difficult.

The positioning of the probes in yaw was accomplished by means of the motor drive arrangement incorporated in the carriage mechanism with control from the console. The yaw seeking feature of the automatic data acquisition system was not used.

It was decided to set the angular position of the probe by hand since with the automatic nulling device of the data logging system the difference between pressures P_2 and P_3 was not zero, but between about 0.5 and 1.0 inches of water.

The data acquisition procedure at each probe position consisted of:

- a. Rotating the probe in yaw until the ΔP manometer indicated $\Delta P = 0$.
- b. Reading and recording P_t , q and θ .
- c. Moving the probe the desired x increment to the next probe position.

At each probe position the data recorded were:

- a. Point number
- b. Δx (in.)
- c. θ (deg.)
- d. P_t (in. of H_2O)
- e. q (in. of H_2O)

Periodic recordings of plenum temperature ($^{\circ}F$), plenum pressure (in. of 1.75 specific gravity manometer fluid), and atmospheric pressure (in. of Hg) were also made.

The incremental distance Δx that the probe should be moved depends on the rate of change of the pressures (P_t or q) with x . The x increment used for all rotor cascade tests was 0.05 inches for both upper and lower traverses. For the

stator cascade tests the value of Δx along the lower traverse was 0.05 inches. The x increment was increased to 0.10 inches along the upper traverse once it was established that there was very little variation of P_t or q with x .

Since for both stator models and rotor models the blade spacing was four inches, the total x distance traversed for upper and lower data was 12 inches or three blade spacings (six inches either side of the middle position). Inasmuch as some time had to be allowed at each probe position for the water manometers to seek new levels, the time required to obtain a complete set of data was approximately six to seven hours per traverse. With the manual mode of data acquisition, upper and lower traverse data could be taken simultaneously. Data was recorded directly on computer coding forms in the format required by the data reduction computer program.

Two stator cascade tests were made; one at a plenum pressure of 26.3 ± 0.3 inches of H_2O , and one at 11.4 ± 0.4 inches of H_2O . The former was conducted at medium motor speed, blower inlet vanes open, and the latter at low motor speed, blower inlet open. End walls and test section inlet guide vanes were positioned so as to yield a flow angle of zero ahead of the stator models. Test section geometry was the same for both stator model runs. Plenum chamber vent ports were set wide open for the stator profile tests.

Five tests were made with the rotor cascade, namely at inlet flow angles between 56.1° and 68.6° . For each of the tests, the motor was run at medium speed with blower inlet vanes open which yielded a plenum pressure of approximately 26.0 inches of H_2O . With the test section configured for the design flow angle ahead of the cascade, a preliminary run was made at a plenum pressure of about 35.0 inches of H_2O . To obtain this plenum pressure, high motor speed was used with blower inlet vanes adjusted to yield 35.0 inches of H_2O pressure in the plenum. Plenum chamber vent ports were full open. At this setting, however, plenum pressure fluctuated ± 0.45 inches of H_2O , and the static pressure readings on the 97-inch manometer banks had a periodic fluctuation of approximately 0.75 inches of water. This was considered excessive in view of the fact that static pressure fluctuations at the intermediate plenum pressure were less than ± 0.2 inches of water. The decision was therefore made to conduct the rotor profile tests at a plenum pressure of approximately 25.0 inches of H_2O .

Rotor profile tests subsequent to the initial test at near design inlet flow angle involved changing the test section end wall angles and adjustment of inlet guide vanes to give cascade inlet flow angles greater than and less than design flow angle.

At the completion of each run, the data sheets were submitted to the computer facility where the data was punched on IBM cards for use as input to the data reduction computer program.

Surveys of the flow conditions across the blade channel at the discharge were conducted for both rotor and stator blading. The vernier probe holder with the pitot-static probe was aligned so that the probe would traverse across the discharge throat area of the blade channel at the mid-span of the blade model. The incremental distance that the probe was moved, total pressure, and static pressure were recorded for each probe position. At the completion of the throat area traverses with the pitot-static probe, the thinner total pressure probe was installed and total pressure readings close to the blade surfaces were recorded in an effort to define the boundary layer thicknesses at the throat station. The above surveys were made at a blade channel adjacent to the central blade in the cascade.

5. Results and Discussion

The results of the cascade tests are given in Appendix C. Tables 1 and 2 are summaries of these results.

The Reynold's number for both stator and rotor cascade is

$$Re_y = \frac{\rho_3 V_3 c}{\mu}$$

Table 1
STATOR CASCADE TEST RESULTS

RUN #	300	301
ζ	0.045	0.051
ζ'	0.044	0.049
α_i°	0.3	0.0
α_o°	0.3	0.0
α_z°	78.5	78.7
$\Delta\alpha^\circ$	78.2	78.7
Cl_∞	2.30	2.30
Cd_∞	0.095	0.133
Rey	1.22×10^6	0.81×10^6
M_3	0.3	0.2
$\sim \theta_1$	± 0.5	0
$\sim \theta_2$	± 0.5	± 0.6

Table 2
ROTOR CASCADE TEST RESULTS

RUN #	302	303	304	305	306
ζ	0.063	0.062	0.081	0.103	0.074
ζ'	0.060	0.059	0.076	0.094	0.070
α_i°	+0.4	+4.2	-2.6	-5.9	+6.6
α_o°	62.4	66.2	59.4	56.1	68.6
α_z°	-71.9	-71.6	-72.4	-71.9	-70.4
$\Delta\alpha^\circ$	134.3	137.3	131.8	128.1	139.0
Cl_∞	5.22	5.86	4.79	4.41	6.29
Cd_∞	0.231	0.233	0.253	0.257	0.277
Rey	1.16×10^6	1.16×10^6	1.12×10^6	1.12×10^6	1.15×10^6
Mo	0.19	0.21	0.16	0.15	0.24
$\sim \theta_1$	± 0.6	± 0.8	± 0.4	± 0.3	± 0.9
$\sim \theta_2$	± 0.3	± 0.4	± 0.2	± 0.2	± 0.2

NOTE: $\sim \theta$ INDICATES THE MAXIMUM VARIATION OF THE MEASURED FLOW ANGLE ALONG THE DISTANCE TRAVERSED

while Mach number is defined as follows:

For the stator cascade,

$$M = \frac{V_3}{\sqrt{\gamma g R T_3}}$$

For the rotor cascade,

$$M = \frac{V_0}{\sqrt{\gamma g R T_0}}$$

Since in turbine calculations and for the turbine tests mentioned earlier, a loss coefficient $\zeta_R = 1 - \Psi^2$

is used, where

$$\Psi = \frac{W_2}{W_{2\text{theoretical}}}$$

a loss coefficient

$$\zeta' = 1 - \left(\frac{V_3}{V_{3\text{theoretical}}} \right)^2$$

is determined for the cascade tests.

The flow conditions in the test section during the stator cascade tests are considered to be good. Fig. C1 shows the static pressure distribution (over three blade spacings) at the lower traverse for Run #300. The maximum static pressure reading was approximately one percent higher than the average static pressure. Fig. C2 shows that the total pressure distribution ahead of the cascade is also quite uniform. The presence of wakes due to the inlet guide vanes is evident in Fig. C3. Since the average value of q_1 , shown in Fig. C3 is about 1.3 inches of water, errors due to fluctuations in pressure, plus errors in measurement form a greater percentage of the true average value of q

than the same for P_s . Therefore, the plot of q_1 versus x is more irregular than that of P_{s1} versus x .

Fig. C5 shows that the flow aft of the cascade is practically mixed by the time it reaches the upper traverse probe location. The constriction factor

$$PSI = \frac{\int_{(1)} p_1 V_1 \cos \theta_1 dx}{\int_{(2)} p_2 V_2 \cos \theta_2 dx} = 1.11$$

indicates that flow constriction due to wall boundary layer growth is not too pronounced. It is reasonable to conclude then, that the flow across the stator cascade is, for all practical purposes, two-dimensional.

Figs. C7 through C12 give corresponding graphs for Run #301. The reason for making a stator cascade test at a lower plenum pressure was to compare the loss coefficients of the same flow at a different Reynold's number. Table 1 shows that the lower loss occurs at the higher Reynold's number, but that the loss coefficients are about the same. Since errors in the pressure readings of Run #301 constitute a greater percentage of the average values, no conclusions can be drawn from the comparison.

Errors in the pressure readings may be classified as:

1. Errors due to the precision limits of the manometer.
2. Errors due to fluctuation in pressure which are caused by a slight unsteady flow condition.

Unless the amplitude and frequency of the pressure fluctuation are known, the accuracy of a reading is difficult to determine. If, however, the fluctuations in pressure are random, statistical methods may be used to estimate an interval in which the actual mean value will lie. This is a so-called confidence interval for the mean.¹ The assumptions made are that the pressure fluctuations are random, and that for a constant plenum pressure, the fluctuations have a normal distribution about the mean value. By observing n pressure readings at the same probe location, a confidence interval is determined by utilizing the t -statistic.²

Let P_m be the mean value of pressure, then

$$\bar{P} - t_{\alpha/2} \frac{S}{\sqrt{n}} < P_m < \bar{P} + t_{\alpha/2} \frac{S}{\sqrt{n}}$$

where

$$\bar{P} = \frac{1}{n} \sum_{i=1}^n P_i$$

$$S^2 = \frac{\sum_{i=1}^n (P_i - \bar{P})^2}{n-1}$$

¹Miller, I., and Freund, J. E., Probability and Statistics for Engineers (Prentice-Hall, Inc., 1965) p. 146.

²Ibid., pp. 136-139.

and S is the variance of the sample of n readings. The quantity $t_{\alpha/2}$ is the value of the t -statistic with a probability of $1-\alpha$ that P_m will fall in the prescribed interval.

Twenty pressure readings of q_2 and P_{t2} were observed. Utilizing the above equations,

$$\bar{q}_2 = 25.20 \quad \text{in. of H}_2\text{O}$$

$$S_{q_2} = \pm 0.06 \quad \text{in. of H}_2\text{O}$$

and

$$25.17 < q_{2\text{mean}} < 25.22 \quad \text{in. of H}_2\text{O}$$

for a 95% confidence interval. This means that for the assumptions made, and for repeated sampling, the mean value of q_2 will be within the interval 95% of the time. By comparison, the variation for the total pressure observations was 0.01 and is considered negligible. It may be assumed further that the variation in pressure is about the same throughout the test section. The statistical method used merely serves to point out that, although the observed variation was 0.06 inches of water (which is small) during the course of a cascade test, the pressure fluctuations are probably less than 0.06 most of the time.

The results of tests made with the actual stator in the

Transonic Turbine Test Rig³ show that the total loss coefficient for the stator or nozzle is generally larger than the value obtained by cascade tests. Values of the stator loss coefficient from actual turbine tests varied from 0.095 to 0.11 for a large range of pressure ratios. The geometric scale factor, cascade models to actual nozzle profiles, is 4.65: 1.

The loss coefficient ζ' accounts for two-dimensional profile losses and mixing losses. The mixing loss is due to the decrement of kinetic energy incurred when the wakes aft of the cascade smooth out to a uniform flow. The mixing loss is included, and the conditions far ahead and far aft are determined because most three-dimensional analyses of axial-flow turbomachines are based on the so-called actuator-disc theory.⁴ According to this theory, it is assumed that the blade row acts as a line of discontinuity at which the flow direction and velocity are changed, and on either side of which, total or stagnation conditions are different.

³Eckert, R. H., Performance Analysis and Initial Tests of a Transonic Turbine Test Rig. (Thesis, United States Naval Postgraduate School, Monterey, California, 1966)

⁴Horlock, J. H., Axial Flow Compressors (London: Butterworths Scientific Publications, 1958) p. 105.

Included in the stator losses of the actual machine are three-dimensional profile loss, secondary flow loss,⁵ wall boundary layer loss and mixing loss. In addition, there is the effect of compressibility which, in this analysis, is undetermined since the flow in the stator of the actual machine was choked for most of the tests.

From a method of turbine performance estimation, based on experimental data, by Ainley and Mathieson, the profile loss coefficient, Y_p , for the stator is predicted to be 0.05. [4] This loss coefficient is defined by

$$Y = \frac{P_{t0} - P_{t3}}{P_{t3} - P_{s3}}$$

Calculating Y from the results of Run #300 (Table C1), it is found that $Y = .049$ which is a loss coefficient based on pressure drop and in which mixing loss is included. The value of Y_p derived by the method of Ainley and Mathieson and the value of Y , from cascade data are close. Although it is generally recognized that mixing losses are small compared to profile loss, the mixing loss is not known from the cascade tests of this investigation.

It would be of interest to know how to correlate the two-dimensional loss obtained from cascade tests to the

⁵Vavra, M. H., Aerothermodynamics and Flow in Turbomachines (New York: John Wiley and Sons, Inc., 1960) pp. 374-384.

overall profile loss of a blade of finite height. N. Scholz suggests that the mean loss coefficient of a cascade is one that accounts also for secondary flow losses due to wall boundary layer. [11] The above reference gives a total loss coefficient as follows:

$$\zeta_{total} = \frac{1}{h} \int_0^h \zeta_{LOCAL}(y) dy = \zeta_{two-dimensional} + \frac{c}{h} \zeta_{wall}$$

Scholz relates the two dimensional loss to the total loss as a function of h/c , the blade aspect ratio. With $\zeta' = .044 = \zeta_{two-dimensional}$ (from Run #300) then from results given by Scholz,

$$\zeta_{total} \cong 0.088$$

for the stator cascade. Now by the method of Ainley and Mathieson,

$$\zeta_s + \zeta_p = 0.088$$

where ζ_s is the secondary flow loss and ζ_p is the profile loss coefficient. This interesting correlation of results suggests areas for future experimental studies with the Cascade Test Facility; namely, the verification of the total cascade loss coefficient relationship given by Scholz, and the effect of Reynold's number on losses near the blade-wall juncture. The latter would be particularly applicable to the prediction of three-dimensional blade loss coefficients of

- ⊕ STATOR PROFILES RUN # 300
- ⊙ ROTOR PROFILES RUN # 302

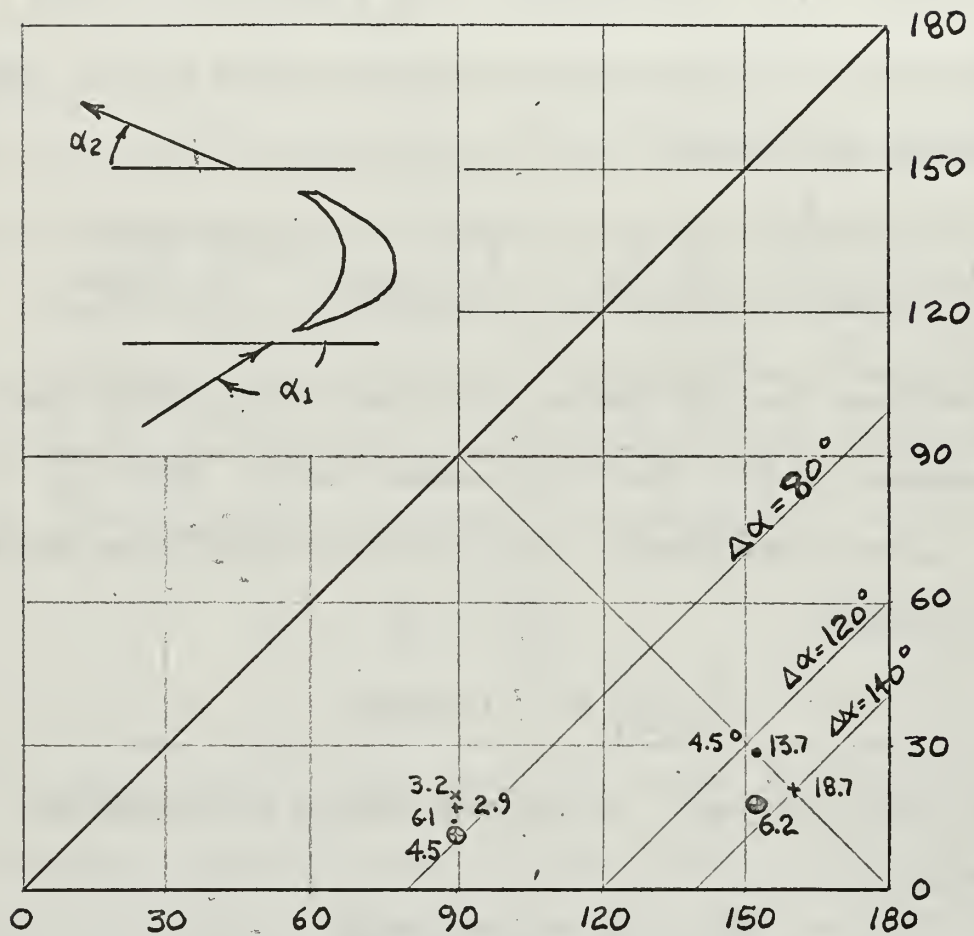


Figure 12

Variation of Loss Coefficients
With Total Flow Deflection

Adapted from Bolte [7]

blade with a varying chord.

Fig. 12 shows the stator cascade loss coefficient with regard to the total turning angle of the flow ($\Delta \alpha$). Also shown are a few loss coefficients for blading of similar deflection as given by Bolte. [7]

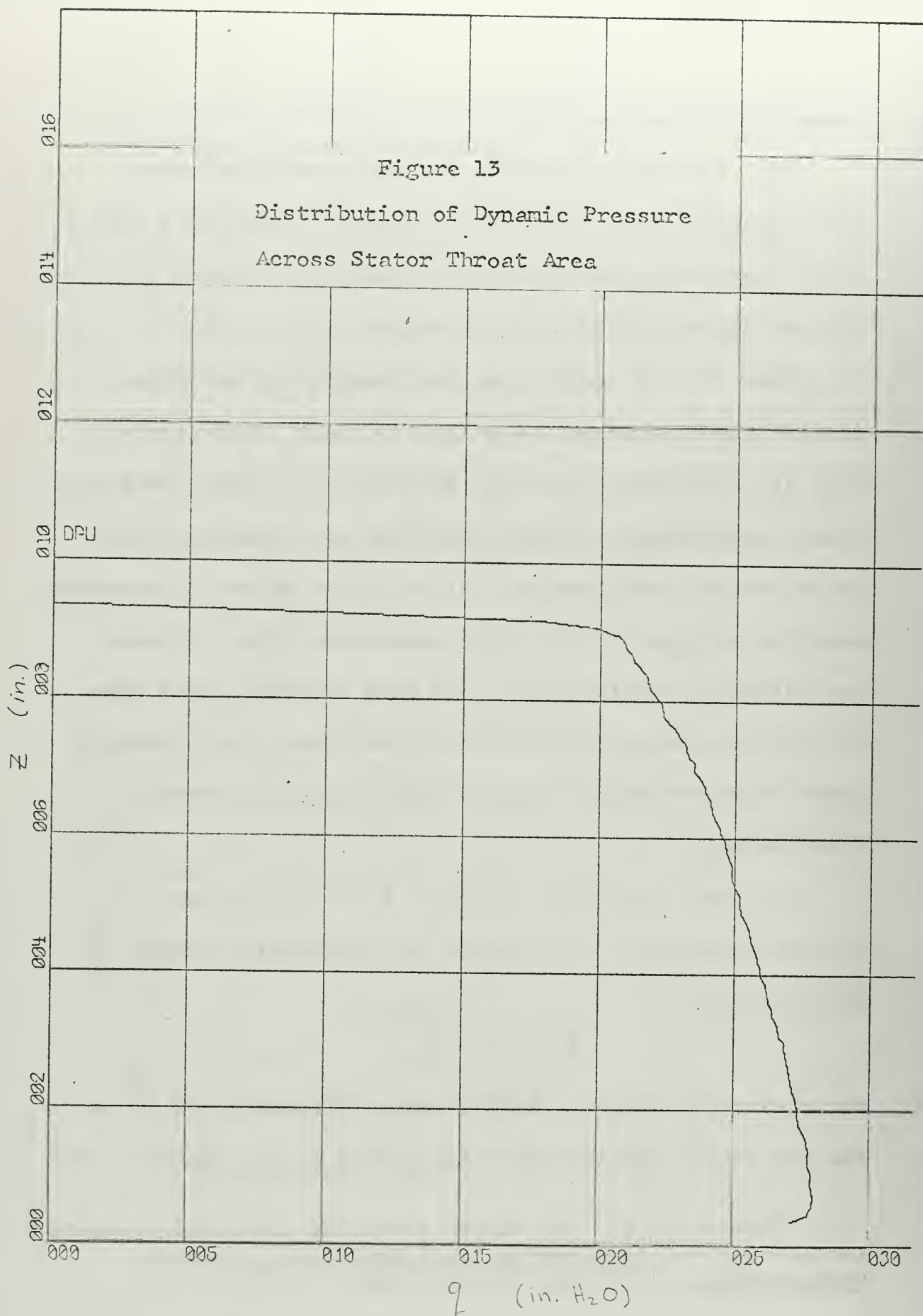
Figs. 13, 14, and 15 are the results of the stator cascade throat area survey using the pitot static probe. Fig. 31, the dynamic pressure distribution across the throat shows the influence of the difference in curvature of the two blade surfaces (see Fig. 9), with the higher q occurring near the surface with the most curvature. Fig. 16 shows the velocity distribution in the wake boundary layer near the trailing edge of the stator blade model. The boundary layer thickness was determined from the total pressure distribution.

The area restriction factor (ξ)⁶ is important to the determination of flow areas in turbomachine design. ξ is defined by

$$\xi = 1 - \frac{\delta^*}{\sigma}$$

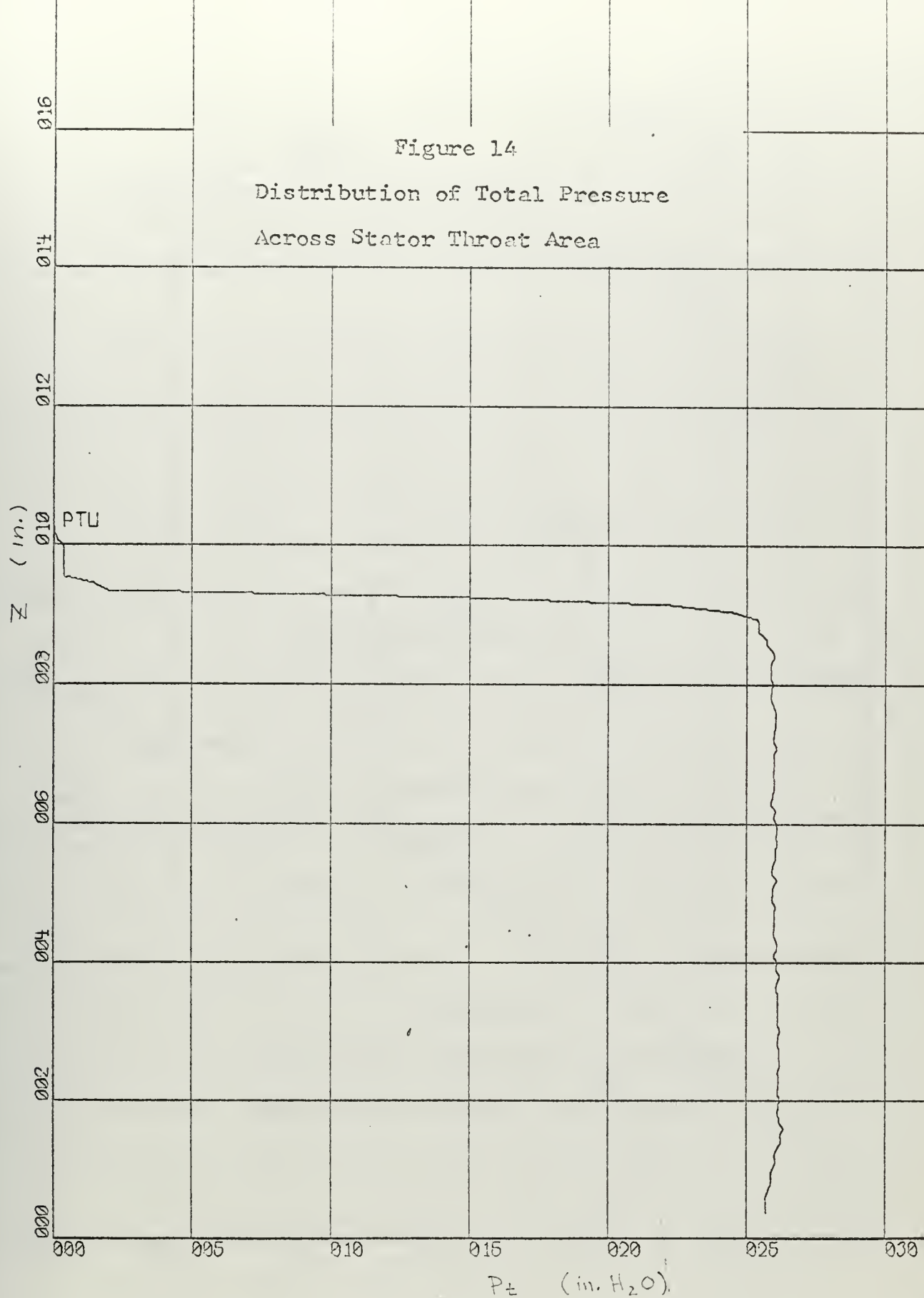
for a cascade, where σ is the throat dimension and δ^* is the sum of the displacement thicknesses in the channel. For

⁶Vavra, M. H. Von Karman Institute for Fluid Dynamics Lecture Series, Problems of Fluid Mechanics in Radial Turbomachines. Part III, March, 1965.



X-SCALE = 5.00E+00 UNITS/INCH.
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STATOR PROFILES

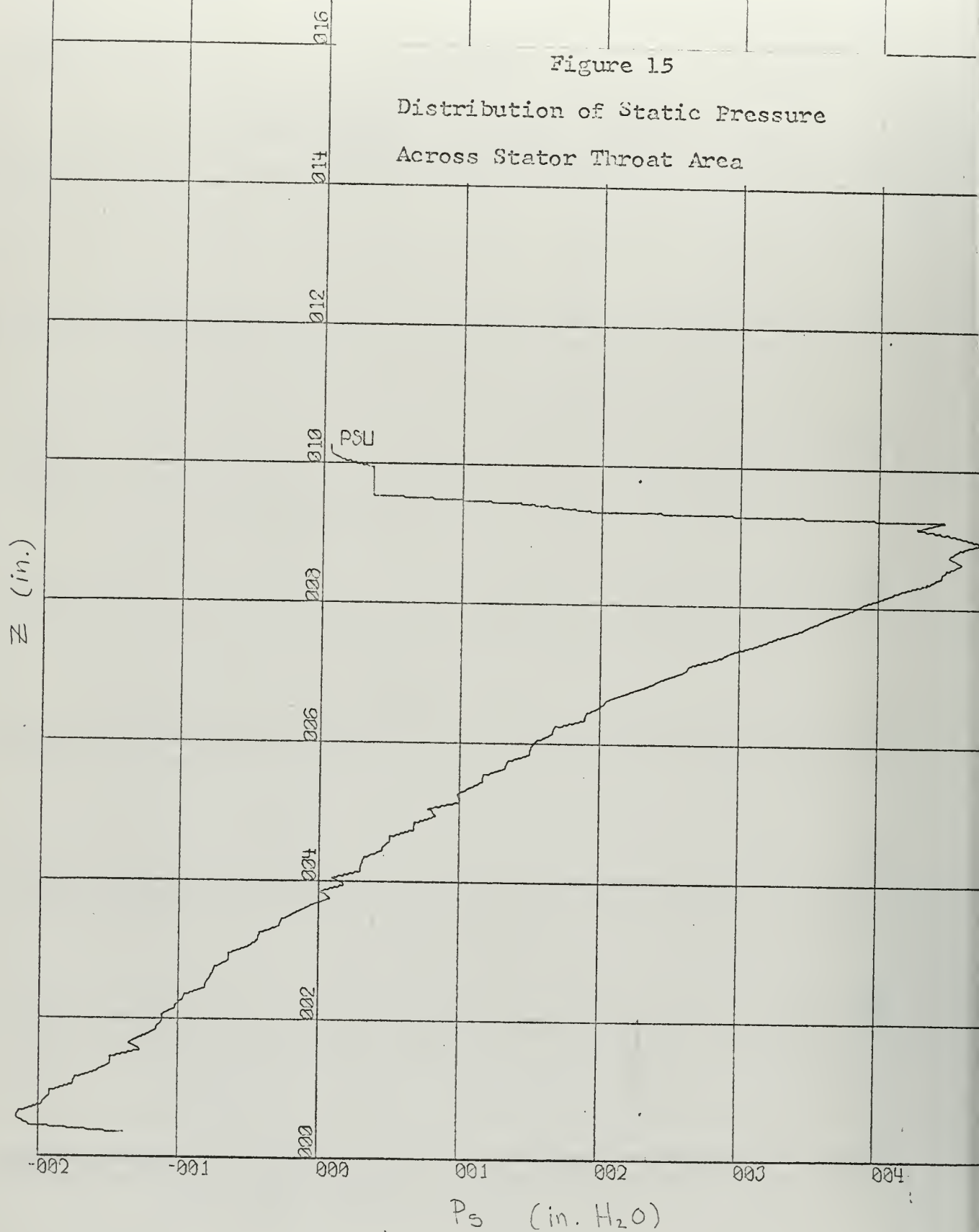


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STATOR PROFILES

Figure 15

Distribution of Static Pressure
Across Stator Throat Area



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Y-SCALE = 2.00E-01 UNITS/INCH.

STATOR PROFILES

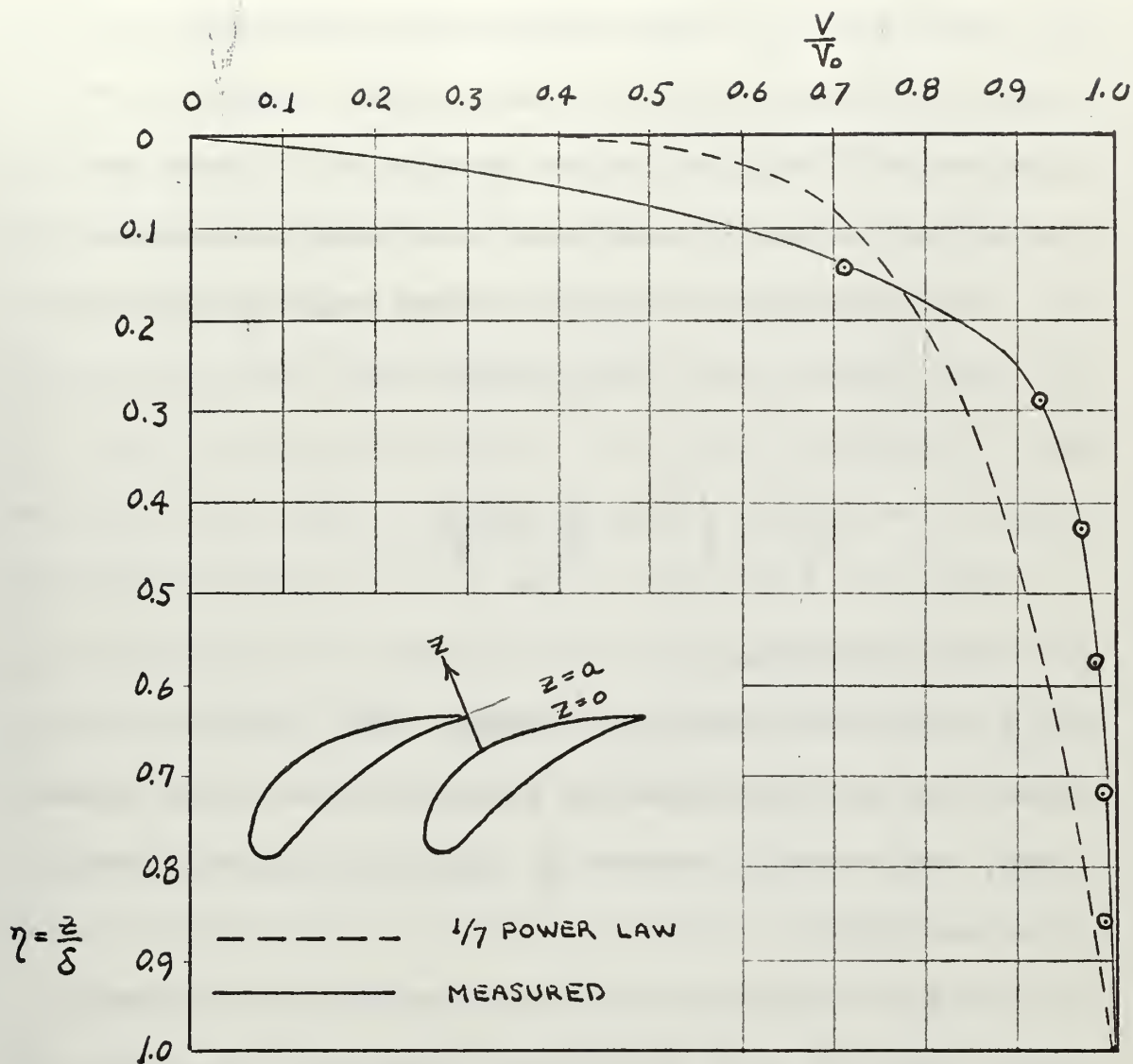


Figure 16
Dimensionless Boundary Layer Velocity
Distribution, Stator Throat Area

the stator cascade, δ^* was estimated by performing a graphical integration of the dimensionless velocity distribution of Fig. 16, and by assuming a 1/7 power law distribution in the vicinity of $z = 0$. From measurement, $\delta = .07$ inches in the vicinity of the trailing edge and $\delta = .056$ inches in the vicinity of $z = 0$.

With

$$\frac{\delta_i^*}{\delta} = \int_0^1 \left(1 - \frac{v}{v_0}\right) d\left(\frac{z}{\delta}\right)$$

and $\sigma = 0.916$ inches,

then $\xi = 0.98$ for the stator cascade. This value is higher than that calculated by Eckert for the actual stator blades. The average value of ξ calculated for the actual stator was 0.95.

The flow conditions in the test section for the rotor cascade tests are also considered to be good. Figs. C13, C19, C25, C31 and C37 all show static pressure distributions ahead of the cascade which are fairly regular. The graphs of q_1 versus x show that the wake patterns due to the inlet guide vanes are not quite as evenly distributed over the distance traversed as they were for the straight inlet guide vanes of the stator cascade. The fact that the flow entering the test section from the plenum must effect a change in direction through the inlet guide vanes probably causes

vortices (associated with the secondary flow through a curved channel). These vortices, in turn, would tend to increase flow turbulence and cause irregularities in the wake patterns at the lower traverse. The values of the constriction factor, however, indicate favorable flow conditions across the cascade.

Fig. 17 shows the change of the loss coefficient with incidence angle. The minimum loss coefficient computed from measured data is 0.06 at $\alpha_i = -4.2^\circ$. Fig. 18 shows the variation of the actual rotor loss coefficient with incidence angle.⁷ The minimum rotor loss coefficient is 0.35 at $\alpha_i = -3.1^\circ$. The loss coefficient ζ for Run #302 is shown also in Fig. 12 for comparison with results from other cascade tests on blading of similar deflection.

Losses in the actual rotor include secondary flow loss, tip losses, three dimensional profile loss, disc friction loss, and an additional loss due to small dead-water regions near the leading edge of the blades close to the tip. Streaks on the rotor blades caused by impurities in the air flow gave evidence of these regions. The loss associated with this phenomenon will be called windage loss. To date, there are no analytical theories that can predict values for

⁷Eckert, op. cit.

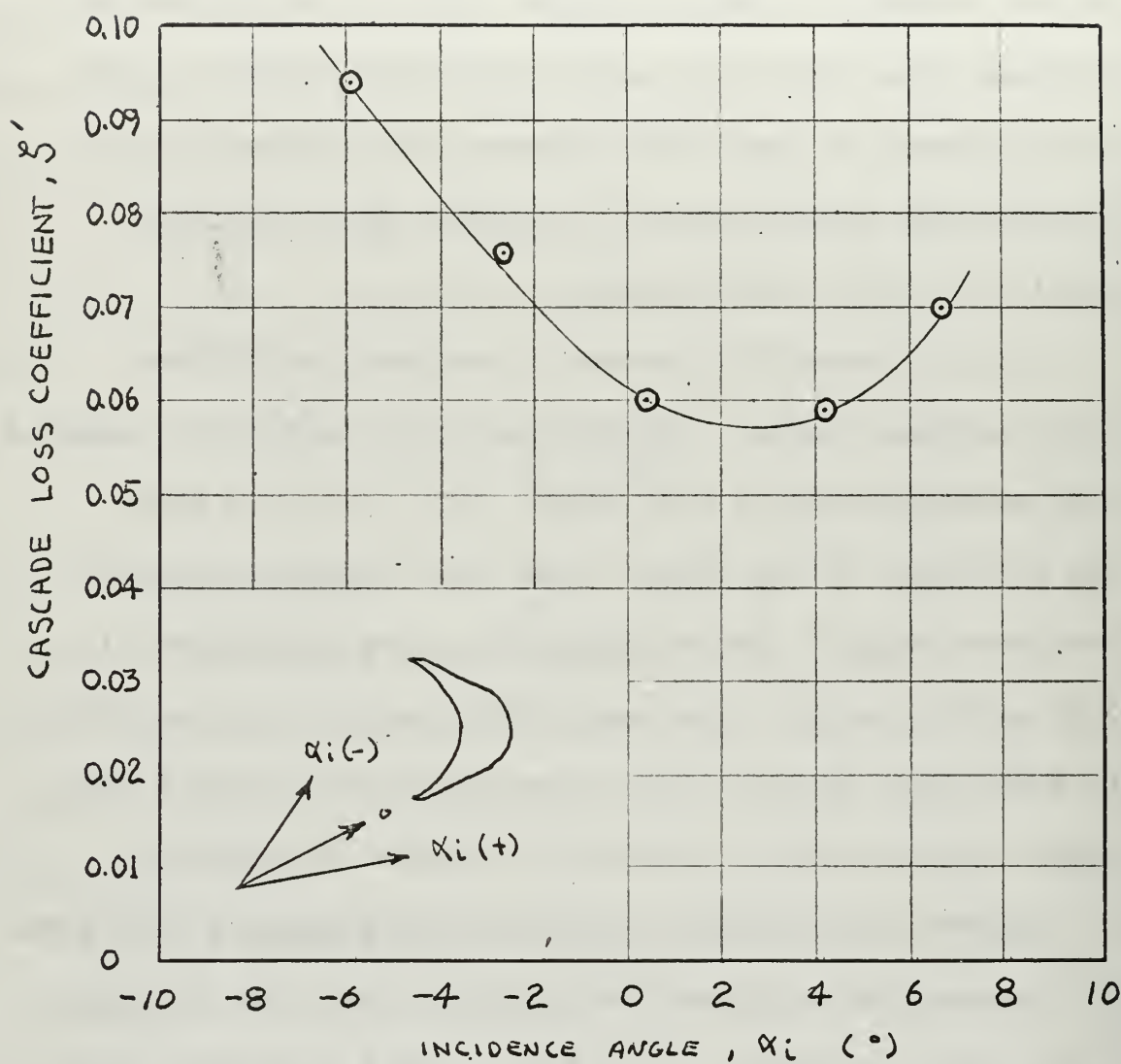


Figure 17
Variation of Rotor Cascade Loss
Coefficient with Incidence Angle

the various losses with any degree of assuredness.

Theoretical methods of loss prediction that are available, and which have demonstrated correlation with experimental tests, are only applicable to blading of small deflection.

The difference in magnitude between loss coefficients obtained from cascade tests and those obtained from turbine tests indicates that profile losses are not the dominant factor in the overall rotor losses.

The assumption is made that the profile and mixing losses that exist in the actual rotor are those that were determined from the cascade tests. The effect of Reynold's number differences is assumed to be negligible. Mach number effects are assumed also to be negligible, although this is not quite true since the Mach number of the rotor was about 0.6 as opposed to about 0.2 for the cascade flow. Let the following loss coefficient be defined

$$\zeta^* = \zeta_R - \zeta'$$

Values of ζ^* were computed from the data of Fig. 17 and Fig. 18. Fig. 19 shows the variation of ζ^* with incidence angle. The losses represented by the quantity ζ^* seem to increase sharply as the incidence angle becomes more positive. The variation of C_{L_∞} with incidence angle (from cascade test data) is also shown in Fig. 19.

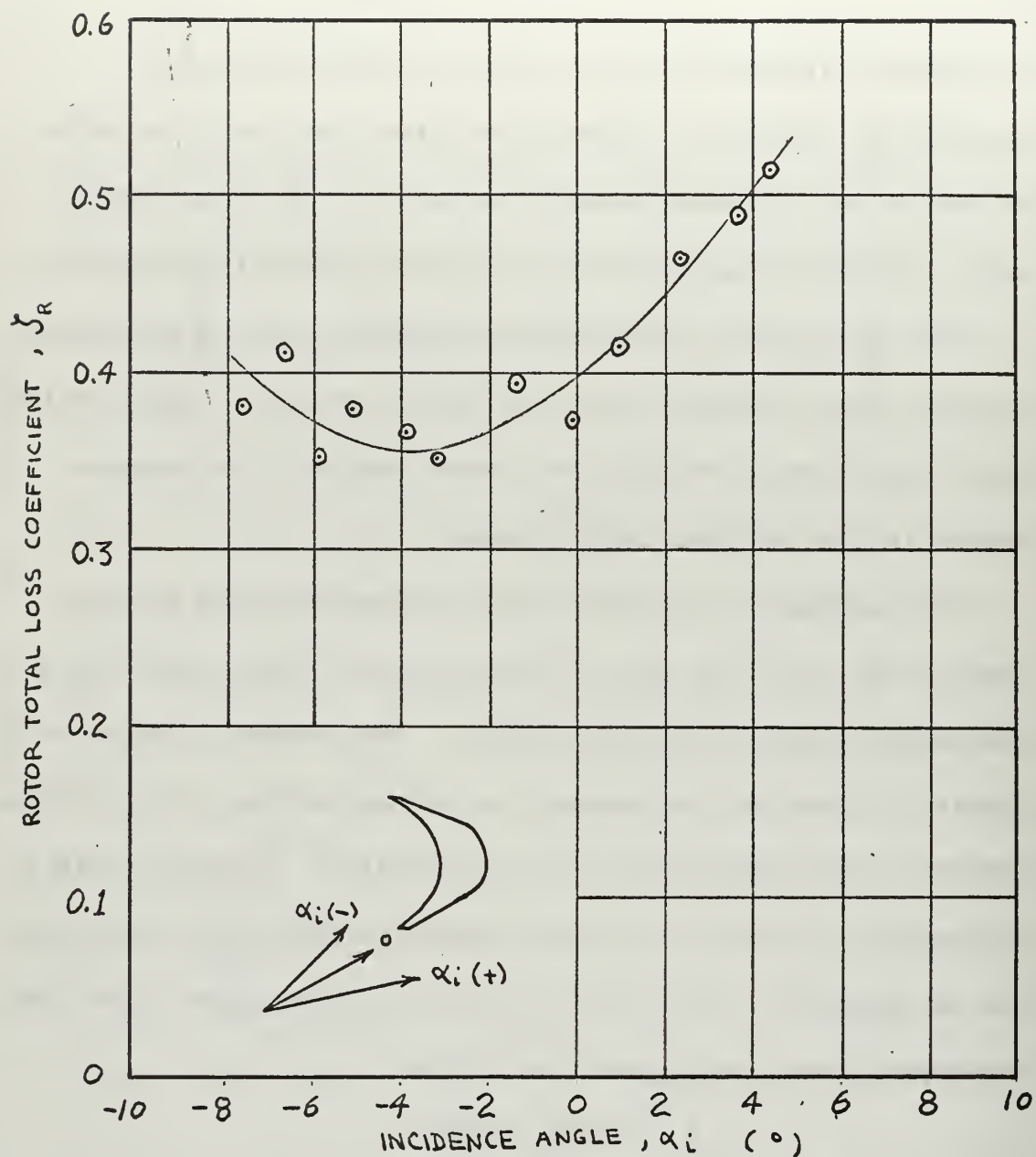


Figure 18

Variation of Actual Rotor Loss
Coefficient with Incidence Angle

Adapted from Eckert [9]

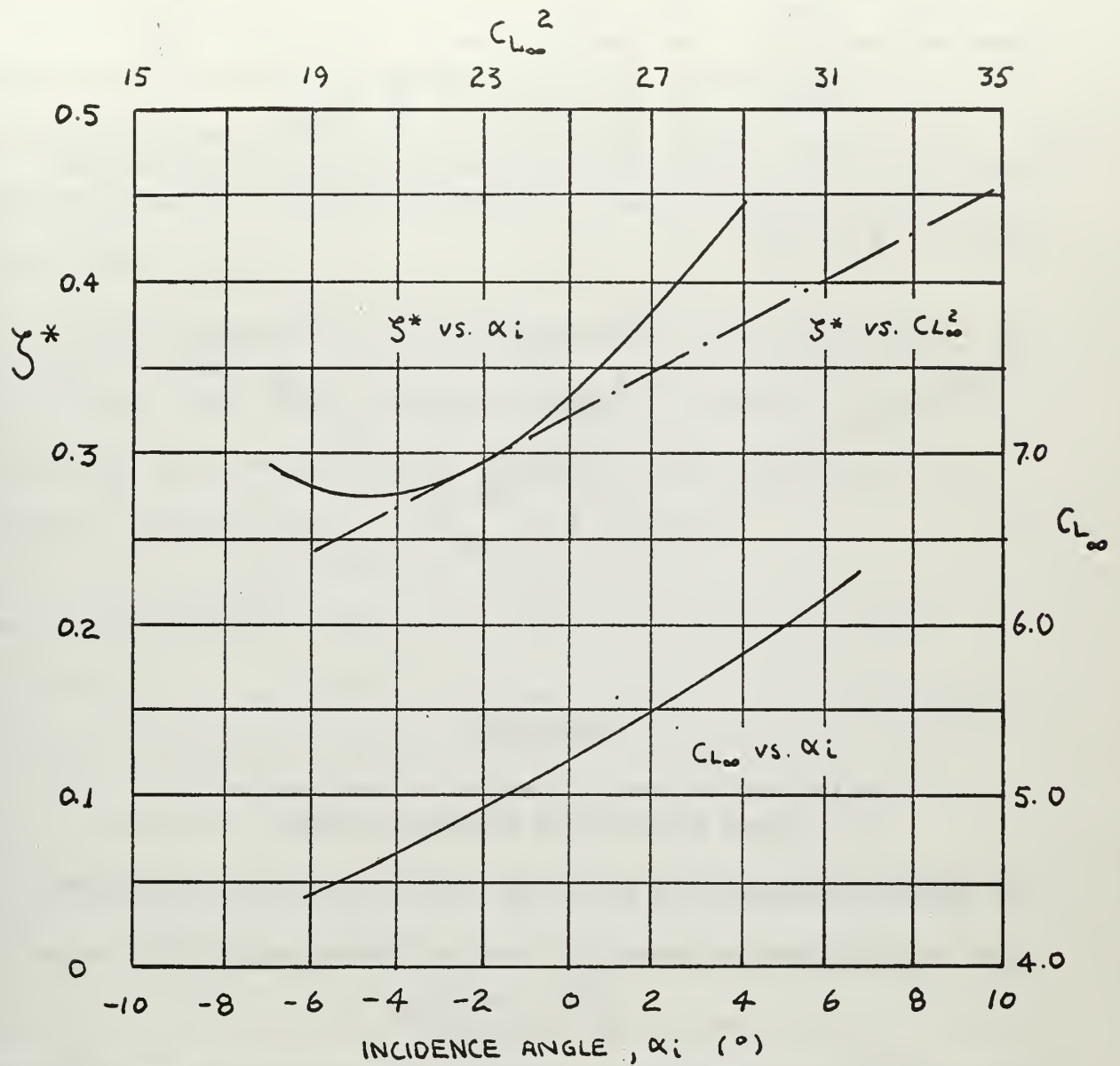


Figure 19

Variation of Loss Coefficient ζ^* with Incidence Angle and the Square of the Lift Coefficient. Variation of Lift Coefficient with Incidence Angle.

An equation that expresses secondary and tip clearance loss in the form of an induced drag coefficient⁸ is

$$C_{Di} = .055 C_{L_{\infty}}^2 \sigma \frac{s}{h} + \frac{1}{4} C_{L_{\infty}}^2 \sigma \frac{\delta}{h} \frac{1}{\cos \beta_2}$$

where δ is the radial tip clearance and β_2 is defined as shown in Fig. 20.

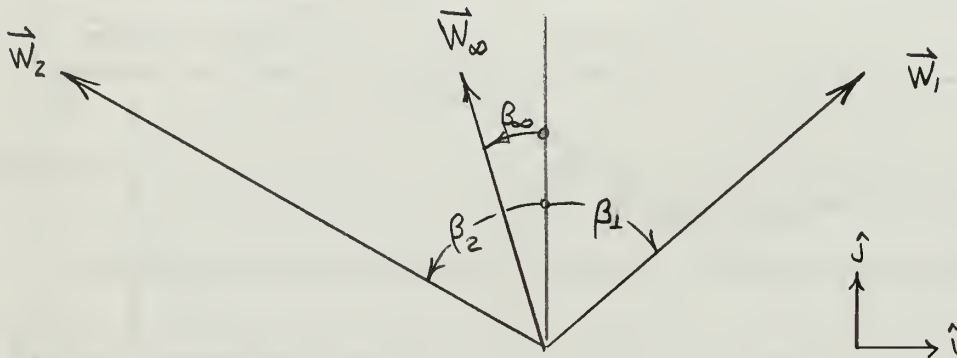


Figure 20

Relative Velocity Diagram of an Impulse Type Axial-Flow Turbine Rotor

The drag coefficient C_{Di} may be converted to an equivalent loss coefficient by means of the following equation⁹

$$C_{Di} = \frac{\zeta^{**} \cos^3 \beta_{\infty}}{\sigma \cos^2 \beta_2}$$

where ζ^{**} is the secondary and tip clearance loss coefficient.

The above two equations combined give,

$$\zeta^{**} = \frac{.055 C_{L_{\infty}}^2}{\cos^3 \beta_{\infty}} \sigma^2 \frac{s}{h} \cos^2 \beta_2 + \frac{1}{4} \frac{C_{L_{\infty}}^2 \sigma^2}{\cos^3 \beta_{\infty}} \frac{\delta}{h} \cos \beta_2$$

⁸Varva, op. cit., p. 379.

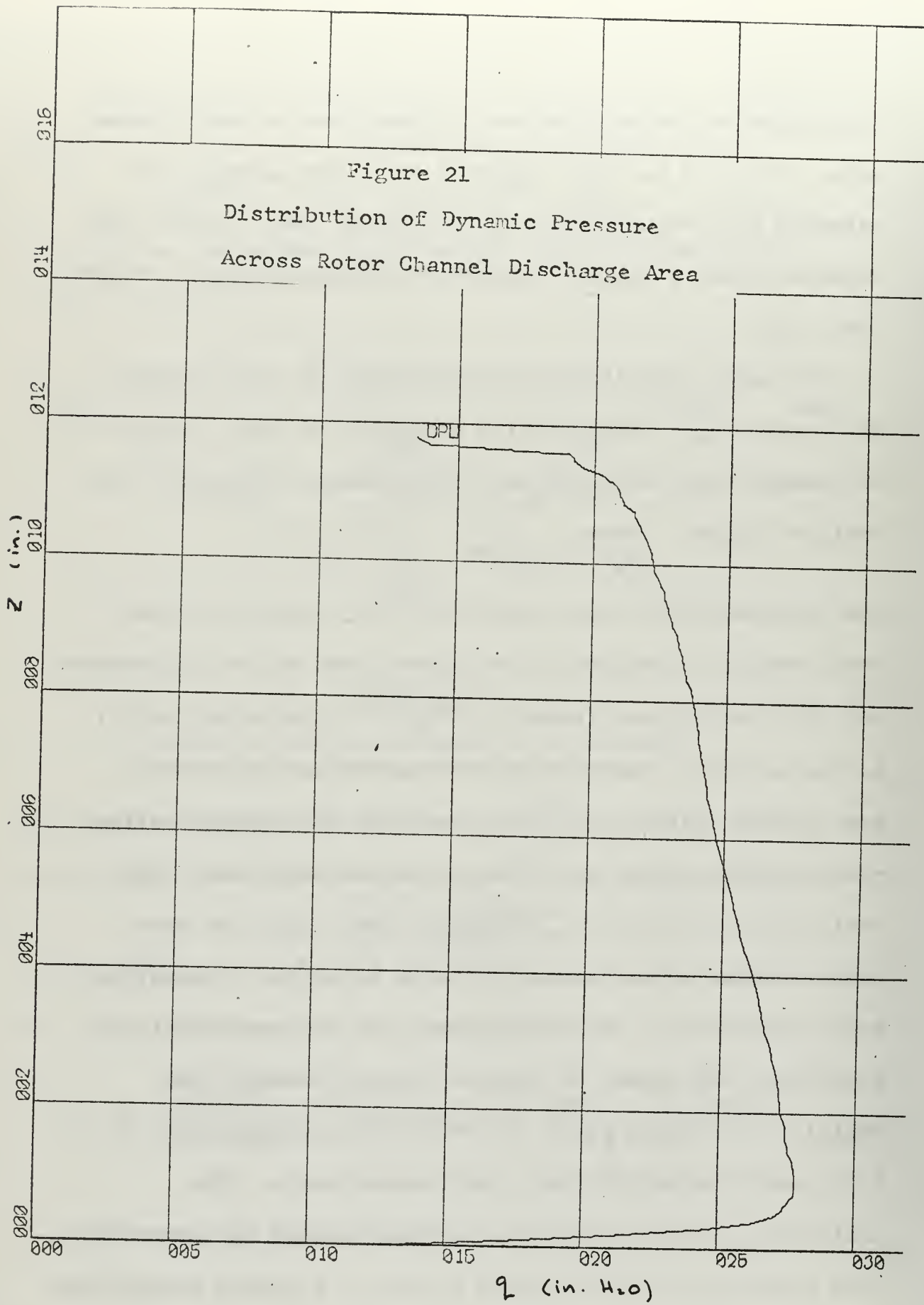
⁹Ibid., p. 336.

This equation has application to blade rows of small camber only, but could possibly supply a basis for an empirical relation for secondary and tip clearance loss. Ainley and Mathieson make a similar suggestion involving only secondary loss. [5]

To make a qualitative determination of the variation of ζ^{**} with $C_{L\infty}^2$, the following procedure is used. First, it is assumed that secondary and tip clearance losses are the dominant losses. Then

$$\zeta^* \cong \zeta^{**}$$

The two-dimensional lift coefficient $C_{L\infty}$ from the cascade test results is assumed to be proportioned to the corresponding lift coefficient (based on $|\vec{W}_\infty|$) of the actual rotor. At the incidence angles which correspond to the cascade test points, values of ζ^* are computed and plotted against corresponding values of $C_{L\infty}^2$ from cascade test data. The variation of ζ^* with $C_{L\infty}^2$ is shown in Fig. 19. The fact that ζ^* seems to be linearly related to $C_{L\infty}^2$ is interesting, but inconclusive. Implied, however, is the possibility of predicting the losses of impulse turbine blading from empirical relations based on the two-dimensional loss and lift coefficients obtained from cascade tests. The facilities for the acquisition of data needed to investigate this possibility are available at the U. S. Naval Postgraduate School, and further studies along these lines should be pursued.

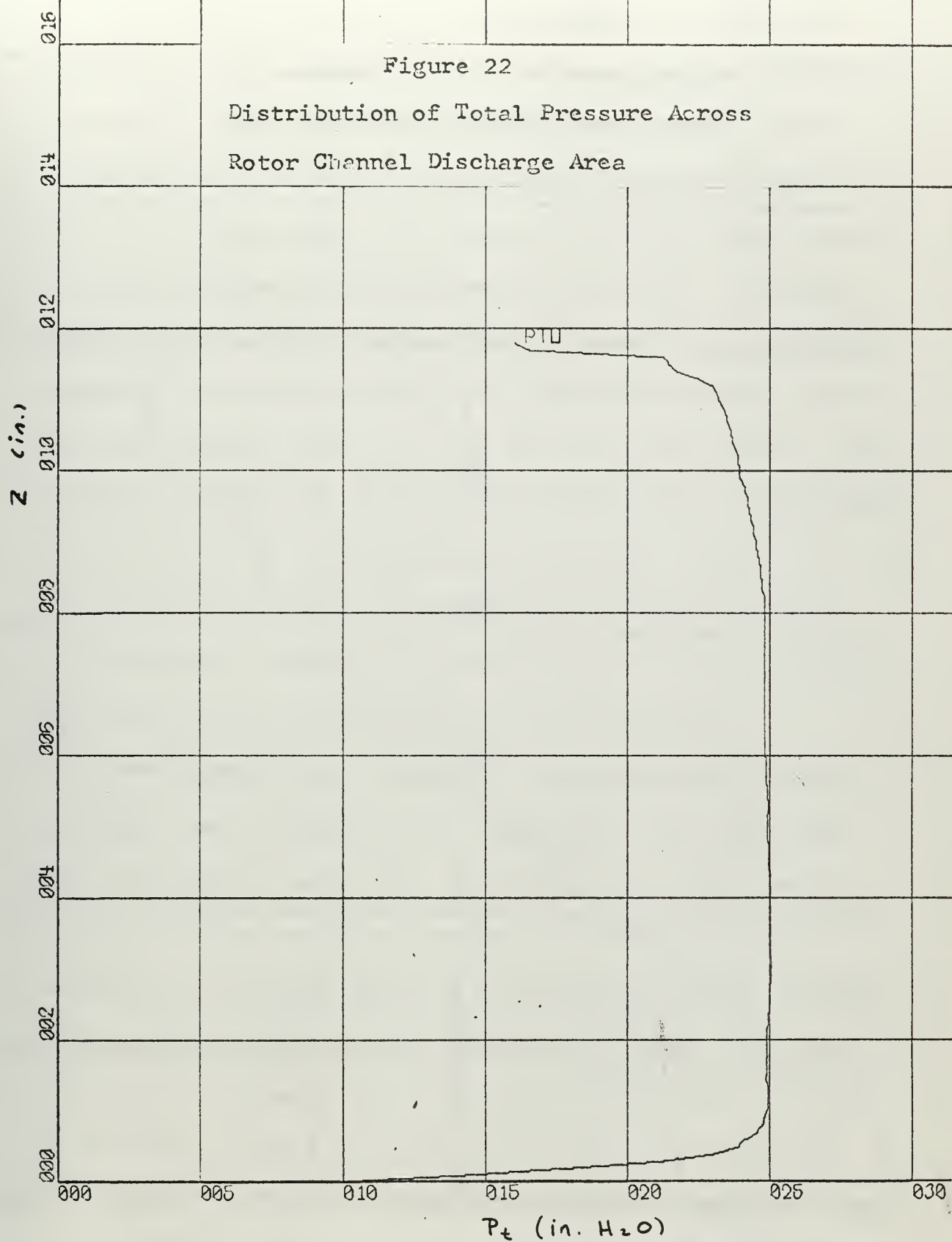


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RUN 302

ROTOR PROFILES



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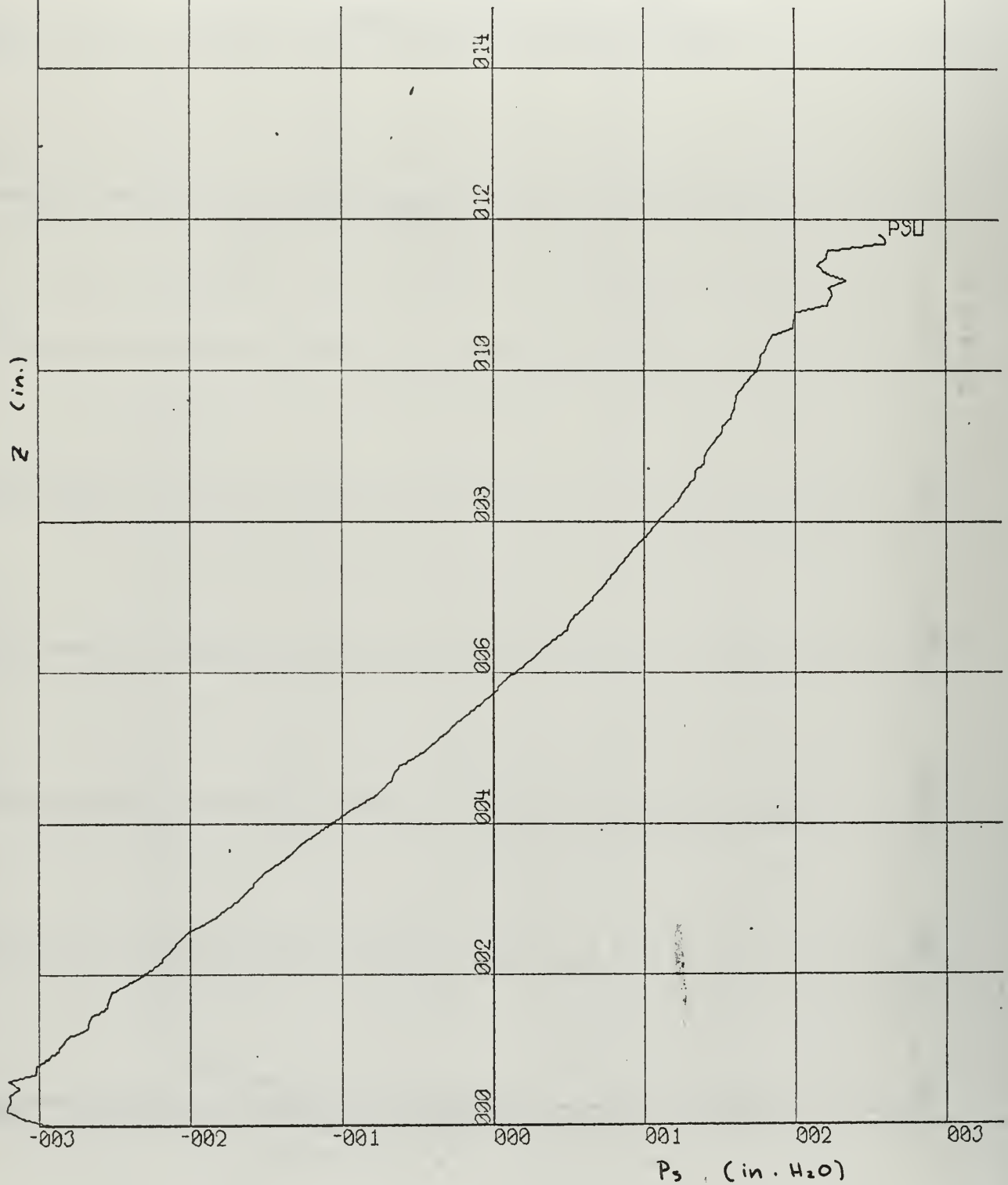
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RUN 302

ROTOR PROFILES

Figure 23

Distribution of Static Pressure
Across Rotor Channel Discharge Area



X-SCALE = 1.00E+00 UNITS/INCH.

Y-SCALE = 2.00E-01 UNITS/INCH.

RUN 302

ROTOR

PROFILES

The results of the flow survey across the discharge area of a rotor cascade blade channel are shown in Figs. 21, 22 and 23. Figs. 24 and 25 are the dimensionless velocity distribution close to the coordinate $z = 0$, and in the wake near the trailing edge. The distributions are based on total pressure readings and the assumption that $\frac{dP_t}{dz} = 0$ in the boundary layer. The boundary layer thickness, δ , is 0.14 inches in the vicinity of $z = 0$, while the boundary layer near the trailing edge ($z = a$) is 0.36 inches thick. The velocity distribution of Fig. 24 indicates that the boundary layer has started to separate from the blade surface. The area restriction factor calculated for the rotor cascade at near design incidence (Run #302) is 0.94. A corresponding value for the actual rotor was not available.

The boundary layer measuring techniques used in this investigation, although crude, demonstrate that this type of investigation can be made because of the large size of the test section and blade models. The use of hot wire anemometry to measure velocity distributions in the boundary layer would eliminate probe interference errors. The fact that the flow appears to be separated at the point $z = 0$ in the blade channel is of interest especially since the loss coefficient is not high. Further investigations of the boundary layer behavior on the blade surface may be of value.

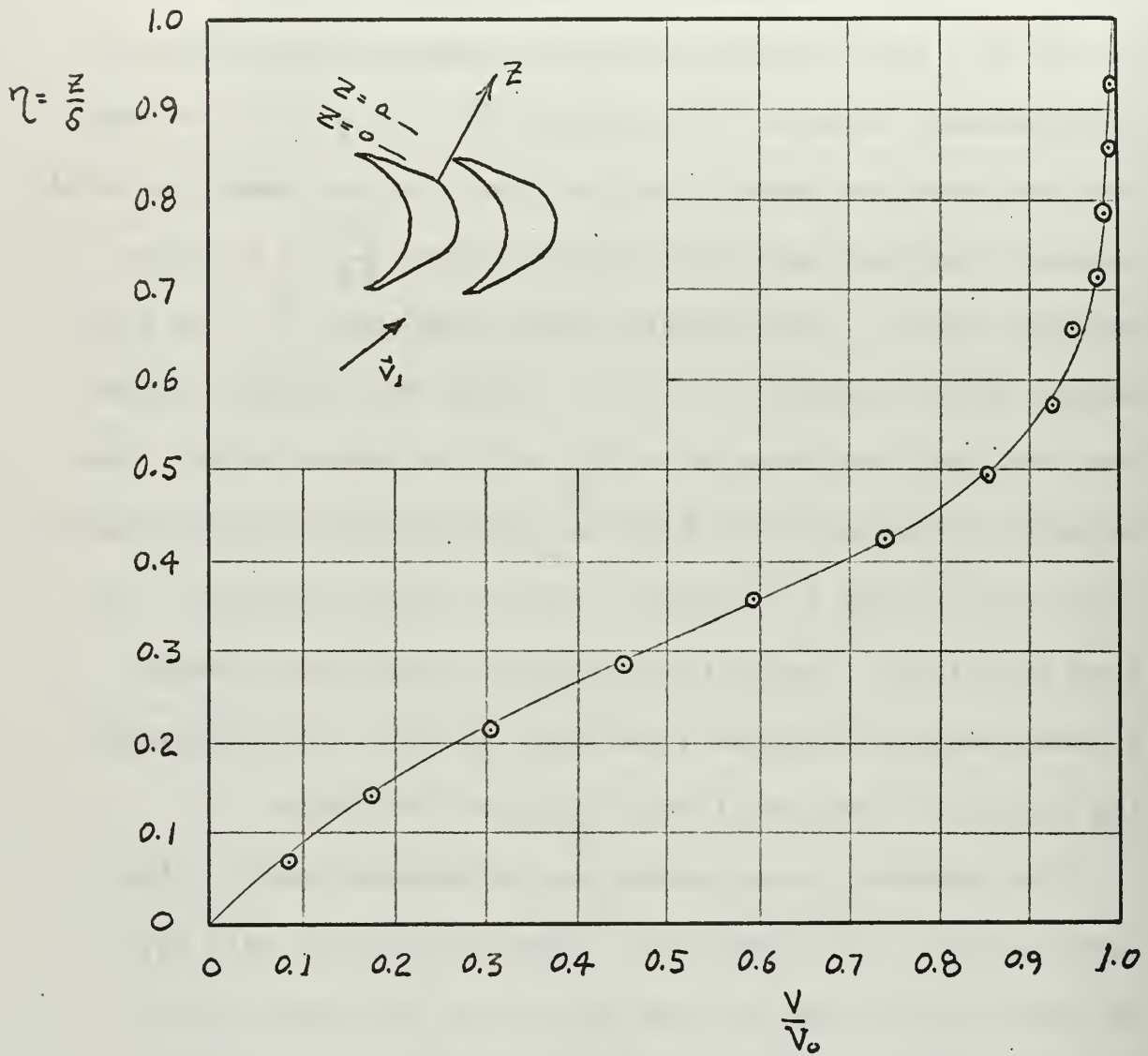


Figure 24

Dimensionless Boundary Layer Velocity
Distribution, Rotor Discharge Area
(in the vicinity of $z = 0$)

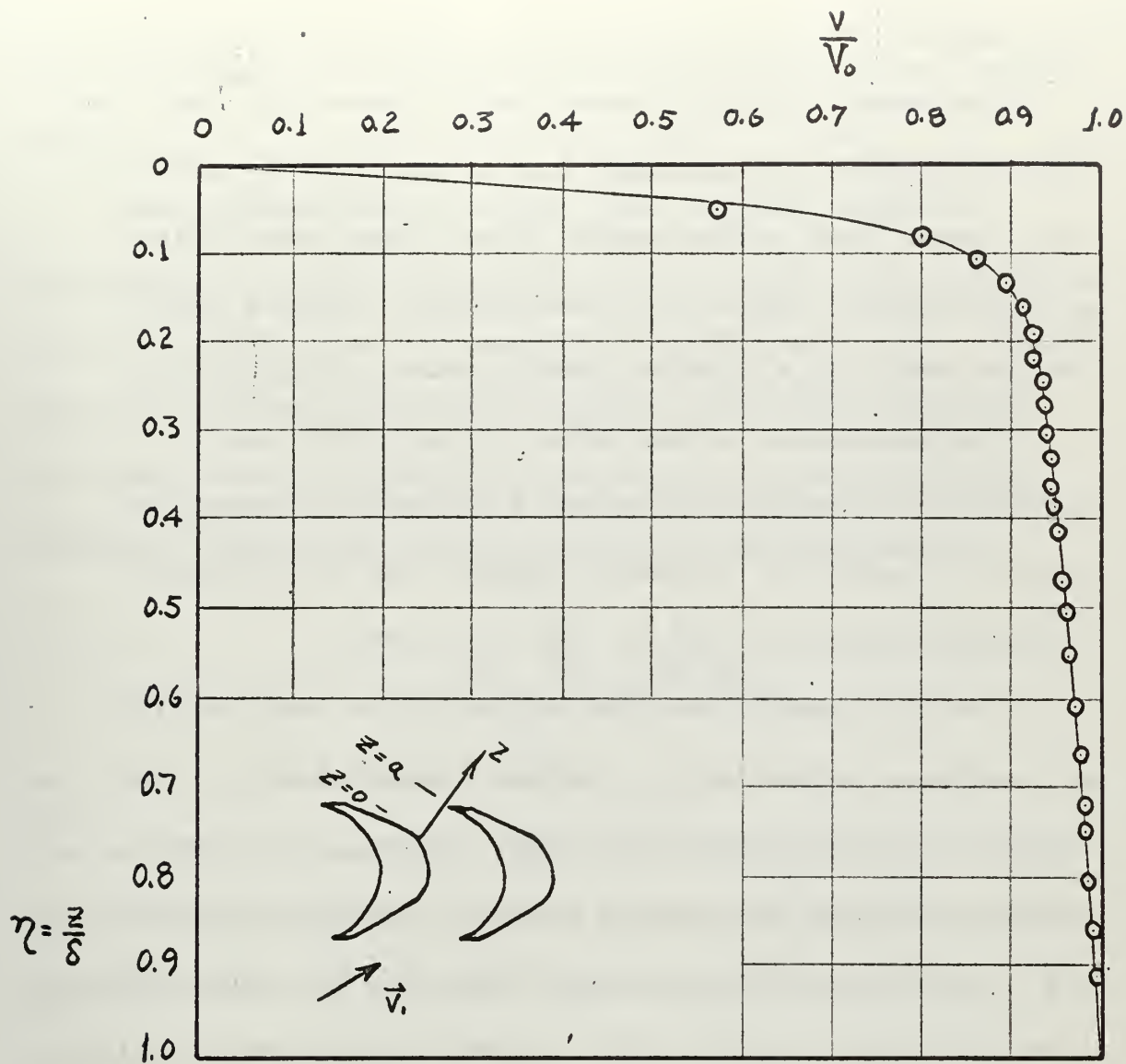


Figure 25

Dimensionless Boundary Layer Velocity
Distribution in the Wake, Rotor Discharge
Area. (In the vicinity of $z = a$)

6. Conclusions

The results of this investigation show that the stator loss coefficient, determined from actual turbine tests with choked flow at the nozzle throat, was about twice as large as the stator loss coefficient obtained from cascade tests at a discharge Mach number of about 0.3.

The percentage of the total actual rotor loss coefficient attributed to profile and mixing losses is greater at negative incidence angles than at positive incidence angles for $-6^\circ < \alpha_i < +6^\circ$.

The flow conditions that exist in the test section are quite satisfactory for turbine cascade tests. The degree of flow non-uniformity that exists in the test section ahead of the cascade depends largely on how much the flow must be deflected after entering the test section from the plenum chamber. The stator cascade test section set-up, with straight inlet guide vanes and end walls positioned vertically, exhibited the most favorable inlet flow conditions.

7. Recommendations and Acknowledgements

As far as the correlation of cascade test results with actual turbine performance is concerned, more can be implied from this investigation than can be definitely concluded. But the implications of any experimental results

must necessarily be the basis of recommendations for future study.

The recommendation is made that cascade tests be performed to measure loss coefficients at planes $y = \text{constant}$ along the blade span. A mean loss coefficient, $\bar{\zeta}$, could then be calculated from the relation previously mentioned as given by Scholz. [11] In like manner, a mean value of incidence angle could be determined by the expression

$$\bar{\alpha}_i = \frac{1}{h} \int_{y=0}^{y=h} \alpha_{i_{\text{LOCAL}}}(y) dy$$

The mean loss coefficient thus calculated would include the influence of secondary flow due to wall boundary layer. Now by varying the angle of the flow ahead of the cascade, the variation of $\bar{\zeta}$ with $\bar{\alpha}_i$ could be established for comparison with actual turbine test data similar to those shown in Fig. 18. This would be a step toward more thorough understanding of the influence of secondary flows on the efficiency of turbine blades of large deflection.

In conjunction with secondary flow investigations, a means of flow visualization in the cascade test section is desirable and recommended. An attempt to introduce smoke streams into the test section was made but was not successful. The smoke, which was generated from heated

mineral oil, "condensed" in the tube that transported it into the air flow. By devising a means to electrically heat the tube, the "condensation" process may be precluded.

In order to separate the loss attributed to mixing from the profile loss, it is recommended that flow conditions aft of the cascade be measured close to the trailing edge of the blade row. A suggestion as to how this might be accomplished is given in the previously mentioned report by the writer. [6]

Acquisition of a hot-wire anemometer probe and associated read-out equipment is recommended for future boundary layer studies of the flow through cascades.

Possible ways of maintaining a constant plenum pressure should be investigated. The first step is to monitor the blower speed and find out if a constant RPM is maintained.

Finally, every effort should be made to utilize the Automatic Data Logging System. In fact, the use of two such systems simultaneously for upper and lower traverse data acquisition would reduce the test time considerably.

The writer wishes to express his appreciation to Mr. R. W. Savage for the patience, loyalty, skill and assistance he provided during the course of this investigation. The writer also wishes to thank Dr. M. H. Vavra for his guidance in this work.

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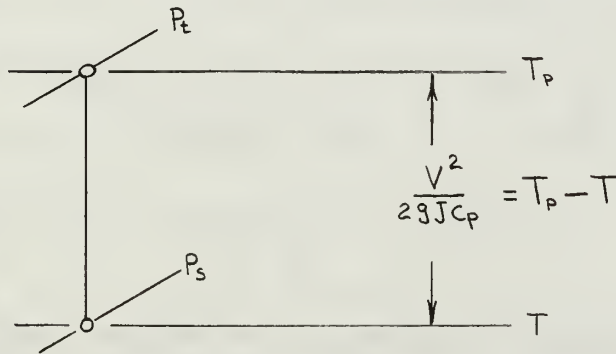
APPENDIX A

DERIVATION OF FORMULAE USED IN THE REDUCTION OF DATA

The recorded results of a cascade test include the following constants: atmospheric pressure (P_{atm}), plenum temperature (T_p), blade spacing (s), blade chord (c), and the number of blade spacings traversed (BN). The coordinate (y) is a constant for a particular run, but is not used in the data reduction.

The following quantities are recorded for both the upper and the lower traverse (stations (1) and (2)), and are functions of the probe position (x): P_t , q , Θ , Δx .

Thermodynamic Relations



Using the isentropic relationship for a perfect gas,

$$P v^\gamma = \text{constant}$$

and

$$c_p = \frac{R}{J} \frac{\gamma}{\gamma - 1}$$

then

$$\frac{V^2}{2gJc_p} = \left[1 - \left(\frac{P_s}{P_t} \right)^{\frac{\gamma-1}{\gamma}} \right] T_p = \frac{(\gamma-1) V^2}{2R\gamma g}$$

with

$$P_s = P_t - q$$

yields

$$V^2 = \gamma g R T_p \frac{2}{\gamma-1} \left[1 - \left(1 - \frac{q}{P_t} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad (1)$$

Let $a_p = \sqrt{\gamma g R T_p}$, where a_p is the sonic velocity in the plenum. Expanding the term $\left(1 - \frac{q}{P_t} \right)^{\frac{\gamma-1}{\gamma}}$ in a binomial expansion and ignoring terms with powers of $\frac{q}{P_t}$ higher than two, $V_1 = V_1(x)$ and $V_2 = V_2(x)$ can be computed. Thus from Eq. (1), the flow velocities as point functions of the probe position along the x coordinate are obtained from

$$V^2 = \frac{2}{\gamma-1} a_p^2 \left[\frac{\gamma-1}{\gamma} \frac{q}{P_t} \left(1 + \frac{1}{2\gamma} \frac{q}{P_t} \right) \right] \quad (2)$$

also, from $\rho = P^{-1/\gamma}$

$$\rho = \rho_t \left(\frac{P_s}{P_t} \right)^{1/\gamma} = \rho_t \left(\frac{P_t - q}{P_t} \right)^{1/\gamma}$$

$$\rho = \rho_t \left(1 - \frac{q}{P_t} \right)^{1/\gamma} \quad (3)$$

With the same binomial expansion as before, and the equation of state for an ideal gas,

$$\rho_t = \frac{P_t}{g R T_p}$$

there is

$$\rho = \frac{P_t}{g R T_p} \left[1 - \frac{1}{\gamma} \frac{q}{P_t} \left(1 + \frac{\gamma-1}{2\gamma} \frac{q}{P_t} \right) \right]$$

or

$$\rho = \frac{P_t}{a_p^2} \left[\gamma - \frac{q}{P_t} \left(1 + \frac{\gamma-1}{2\gamma} \frac{q}{P_t} \right) \right] \quad (4)$$

From Eq. (4), $\rho_1 = \rho_1(x)$ and $\rho_2 = \rho_2(x)$ can be computed.

The static pressures at the lower and upper measuring planes are

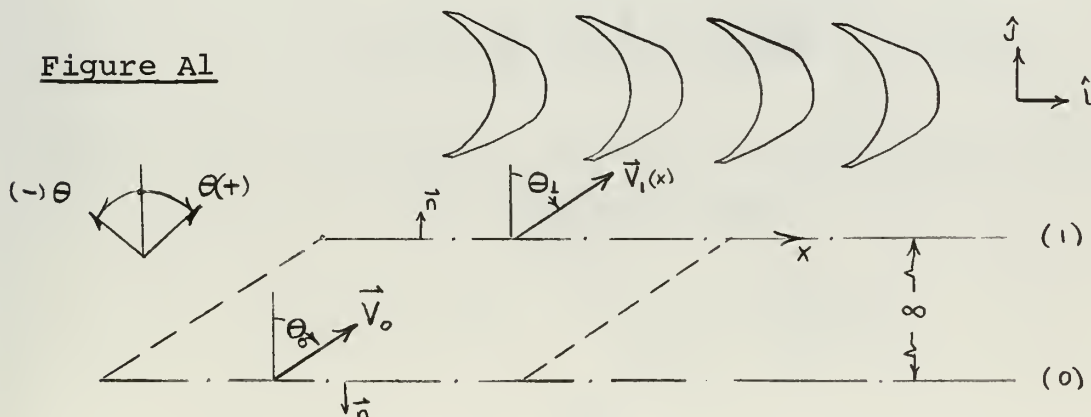
$$P_{s1} = P_{t1} - q_1 \quad \text{and} \quad P_{s2} = P_{t2} - q_2$$

where

$$P_{s1} = P_{s1}(x) \quad \text{and} \quad P_{s2} = P_{s2}(x)$$

Conditions Far Ahead of the Cascade

Up to this point, the derivation of the equations is similar to that given by Rose and Guttormson with only the difference that q is a measured quantity and not P_s . [10] In the determination of the flow character far ahead of the cascade, the above reference makes use of the momentum theorem. The control volume used consisted of two streamlines bounded by the lower measuring plane (1) near the cascade, and of a reference plane far ahead of the cascade (o) at which uniform flow conditions were considered to exist.



The resultant force on the control volume was considered to be equal to zero. Since the flow at station (1) can never be exactly uniform, this model assumed that a flow of uniform conditions was by some means becoming non-uniform without guiding surfaces to cause it to do so. The following derivations will show that this concept violates the energy equation.

Consider the flow between two parallel streamlines, as shown below, where V_1 is constant and $V_2 = f(y)$

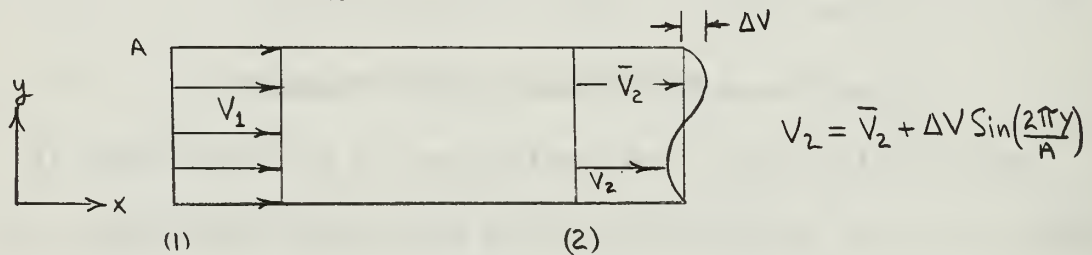


Figure A2

For constant mass densities $\rho = \rho_1 = \rho_2$, from continuity,

$$V_1 = \frac{1}{A} \int_0^A V_2 dy$$

From the Momentum equation in the x-direction, and assuming that the static pressure P_{s2} at station (2) is constant,

$$m_{s1} V_1 - \int_0^A dm_{s2} V_2 + P_{s1} A - P_{s2} A = 0$$

with

$$m_{s1} = \rho V_1 A$$

and

$$dm_{s2} = \rho V_2 dy$$

$$P_{s2} = \rho V_1^2 + P_{s1} - \frac{\rho}{A} \int_0^A V_2^2 dy$$

The average total pressure at station (2) is

$$\bar{P}_{t2} = \frac{\int_0^A (P_{s2} + \frac{\rho}{2} V_2^2) \rho V_2 dy}{\int_0^A \rho V_2 dy} = \frac{\int_0^A (P_{s2} + \frac{\rho}{2} V_2^2) V_2 dy}{AV_1}$$

$$\bar{P}_{t2} = \frac{P_{s2} \int_0^A V_2 dy}{AV_1} + \frac{\frac{\rho}{2} \int_0^A V_2^3 dy}{AV_1} = P_{s2} + \frac{\rho}{2} \frac{\int_0^A V_2^3 dy}{AV_1}$$

Further,

$$P_{t2} = \rho V_1^2 + P_{s1} - \frac{\rho}{A} \int_0^A V_2^2 dy + \frac{\rho}{2A} \int_0^A \frac{V_2^3}{V_1} dy$$

with $P_{t1} = \frac{\rho}{2} V_1^2 + P_{s1}$

$$\bar{P}_{t2} = P_{t1} + \frac{\rho}{2} V_1^2 - \frac{\rho}{A} \int_0^A V_2^2 dy + \frac{\rho}{2A} \int_0^A \frac{V_2^3}{V_1} dy$$

Assume now that, as shown in Fig. A2,

$$V_2 = \bar{V}_2 + \Delta V \sin\left(\frac{2\pi y}{A}\right)$$

Clearly, $\bar{V}_2 = V_1$ from the equation of continuity, and, with

$$a = \frac{\Delta V}{\bar{V}_2}$$

$$V_2 = V_1 \left[1 + a \sin\left(\frac{2\pi y}{A}\right) \right]$$

then,

$$\begin{aligned} \bar{P}_{t2} = P_{t1} + \frac{\rho}{2} V_1^2 - \frac{\rho}{A} \int_0^A V_1^2 \left[1 + 2a \sin\left(\frac{2\pi y}{A}\right) + a^2 \sin^2\left(\frac{2\pi y}{A}\right) \right] dy \\ + \frac{\rho}{V_1 2A} \int_0^A V_1^3 \left[1 + 3a \sin\left(\frac{2\pi y}{A}\right) + 3a^2 \sin^2\left(\frac{2\pi y}{A}\right) + a^3 \sin^3\left(\frac{2\pi y}{A}\right) \right] dy \end{aligned}$$

and,

$$\bar{P}_{t2} = P_{t1} + \frac{\rho}{2} V_1^2 \left(\frac{5}{2} a^2 \right)$$

Thus $P_{t2} > P_{t1}$ for $a \neq 0$

Conditions far ahead of the cascade are assumed to be the average values of the conditions measured at the lower measuring plane (1). The following quantities are obtained:

$$P_{s0} = \frac{\int_{(1)} P_{s1} V_1 \cos \theta_1 dx}{\int_{(1)} V_1 \cos \theta_1 dx} \quad (5)$$

$$P_{t0} = \frac{\int_{(1)} P_{t1} V_1 \cos \theta_1 dx}{\int_{(1)} V_1 \cos \theta_1 dx} \quad (6)$$

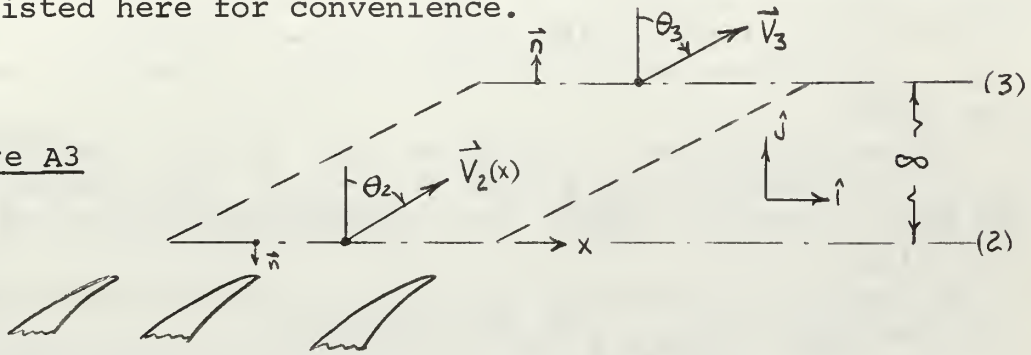
$$e_0 = \frac{1}{\Delta X_1} \int_{(1)} e_1 dx \quad (7)$$

$$\theta_0 = \frac{1}{\Delta X_1} \int_{(1)} \theta_1 dx \quad (8)$$

Conditions Far Aft of the Cascade

The derivation of the following relations is given in [10] and listed here for convenience.

Figure A3



From the Momentum equation:

$$\int_{(2)} dm_{s_2} \vec{V}_2 - \int_{(3)} dm_s \vec{V}_3 + \hat{j} \int_{(2)} P_{s_2} dx - \hat{j} \int_{(3)} P_{s_3} dx = 0 \quad (9)$$

From continuity

$$ms = \int_{(2)} \rho_2 V_2 \cos \theta_2 dx = \rho_3 \Delta X_3 V_3 \cos \theta_3 \quad (10)$$

$$\vec{V}_2 = \hat{i} V_2 \sin \theta_2 + \hat{j} V_2 \cos \theta_2$$

$$\vec{V}_3 = \hat{i} V_3 \sin \theta_3 + \hat{j} V_3 \cos \theta_3$$

Substituting the above relations in Eq. (9),

$$\begin{aligned} \int_{(2)} \rho_2 V_2 \cos \theta_2 (\hat{i} V_2 \sin \theta_2 + \hat{j} V_2 \cos \theta_2) dx - ms (\hat{i} V_3 \sin \theta_3 + \hat{j} V_3 \cos \theta_3) \\ \stackrel{(1)}{=} \hat{j} P_{s_3} \Delta X_3 - \hat{j} \int_{(2)} P_{s_2} dx \end{aligned} \quad (11)$$

The \hat{i} components of Eq. (11) give

$$\int_{(2)} \rho_2 V_2^2 \cos \theta_2 \sin \theta_2 dx = ms V_3 \sin \theta_3$$

With Eq. (10)

$$V_3 \sin \theta_3 = \frac{\frac{1}{2} \int_{(2)} \rho_2 V_2^2 \sin 2\theta_2 dx}{\int_{(2)} \rho_2 V_2 \cos \theta_2 dx} \quad (12)$$

The \hat{j} components of Eq. (11) give

$$\int_{(2)} \rho_2 V_2^2 \cos^2 \theta_2 dx - m_s V_3 \cos \theta_3 = P_{s3} \Delta X_3 - \int_{(2)} P_{s2} dx$$

with Eq. (10),

$$P_{s3} = \frac{1}{\Delta X} \int_{(2)} \rho_2 V_2^2 \cos^2 \theta_2 dx + \frac{1}{\Delta X_3} \int_{(2)} P_{s2} dx - \frac{1}{\rho_3 (\Delta X)^2} \left[\int_{(2)} \rho_2 V_2 \cos \theta_2 dx \right]^2 \quad (13)$$

From Eq. (10)

$$V_3 \cos \theta_3 = \frac{1}{\rho_3 \Delta X_3} \int_{(2)} \rho_2 V_2 \cos \theta_2 dx \quad (14)$$

Eqs. (12) and (14) combined, give

$$V_3^2 = \frac{1}{4} \frac{\left[\int_{(2)} \rho_2 V_2^2 \sin 2\theta_2 dx \right]^2}{\left[\int_{(2)} \rho_2 V_2 \cos \theta_2 dx \right]} + \frac{1}{\rho_3^2 (\Delta X)^2} \left[\int_{(2)} \rho_2 V_2 \cos \theta_2 dx \right]^2 \quad (15)$$

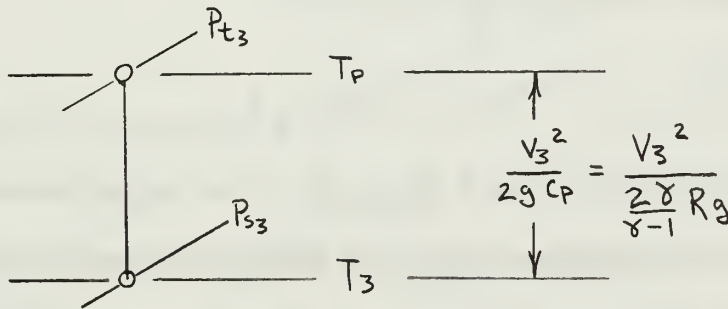
and,

$$\theta_3 = \arctan \left\{ \frac{\rho_3 \Delta X_3}{2} \frac{\int_{(2)} \rho_2 V_2^2 \sin 2\theta_2 dx}{\left[\int_{(2)} \rho_2 V_2 \cos \theta_2 dx \right]^2} \right\} \quad (16)$$

$$\Delta X_3 = \Delta X_2$$

The Mass Density Far Aft of the Cascade

The assumption of constant density between stations (2) and (3) is usually made in view of the fact that the mixing losses are small. Hence, the difference between (V_3) and the average velocity (V_2) is small. However, since the whole data reduction procedure of this study attempts to take into account compressibility effects, an iteration procedure to determine ρ_3 is used.



There are:

$$T_p - T_3 = \frac{\gamma-1}{2\gamma Rg} \frac{V_3^2}{T_p}$$

$$\frac{T}{T_p} = \left[\frac{P_{s3}}{P_{t3}} \right]^{\frac{\gamma-1}{\gamma}} = 1 - \frac{\gamma-1}{2} \frac{V_3^2}{\gamma g R T_p}$$

and,

$$\frac{P_{s3}}{P_{t3}} = \left[1 - \frac{\gamma-1}{2} \frac{V_3^2}{a_p^2} \right]^{\frac{\gamma}{\gamma-1}} \quad (17)$$

also,

$$\frac{P_{s3}}{P_{t3}} = \left[\frac{\rho_3}{\rho_t} \right]^{\gamma} = \left[\frac{\rho_3 g R T_p}{P_{t3}} \right]^{\gamma}$$

and,

$$e_3 = \left(\frac{P_s}{P_t} \right)^{1/8} \frac{P_t}{g R T_P}$$

Let $e_3 = e_3'$ then with

$$\frac{P_s}{P_t} = 1 - \frac{(P_t - P_s)}{P_t}$$

then,

$$e_3' = \frac{P_{t3}}{g R T_P} \left[1 - \frac{(P_{t3} - P_{s3})}{P_{t3}} \right]^{1/8}$$

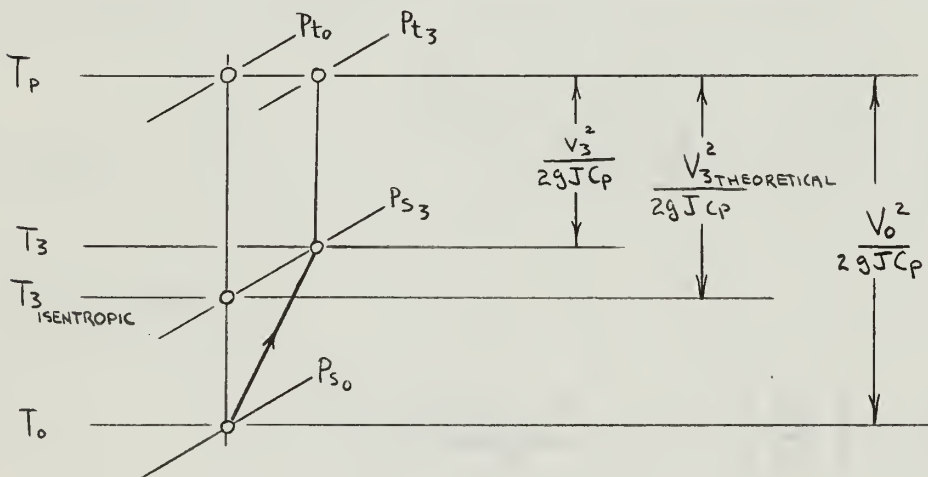
By selecting a trial value of e_3 , with the measured quantities at station (2) and Eqs. (15) and (13), V_3^2 and P_{s3} are calculated. Then, with Eq. (17),

$$P_{t3} = P_{s3} / (P_{s3}/P_{t3})$$

Now, with the values of P_{s3} and P_{t3} , e_3' is calculated from Eq. (18). When the absolute value of the difference between e_3' and the trial value of e_3 is less than or equal to a pre-selected tolerance, the value of e_3 is established.

Loss Coefficients

Considering first a compressor cascade



Let: $\gamma = \frac{V_{3\text{THEORET}}^2 - V_3^2}{V_3^2}$

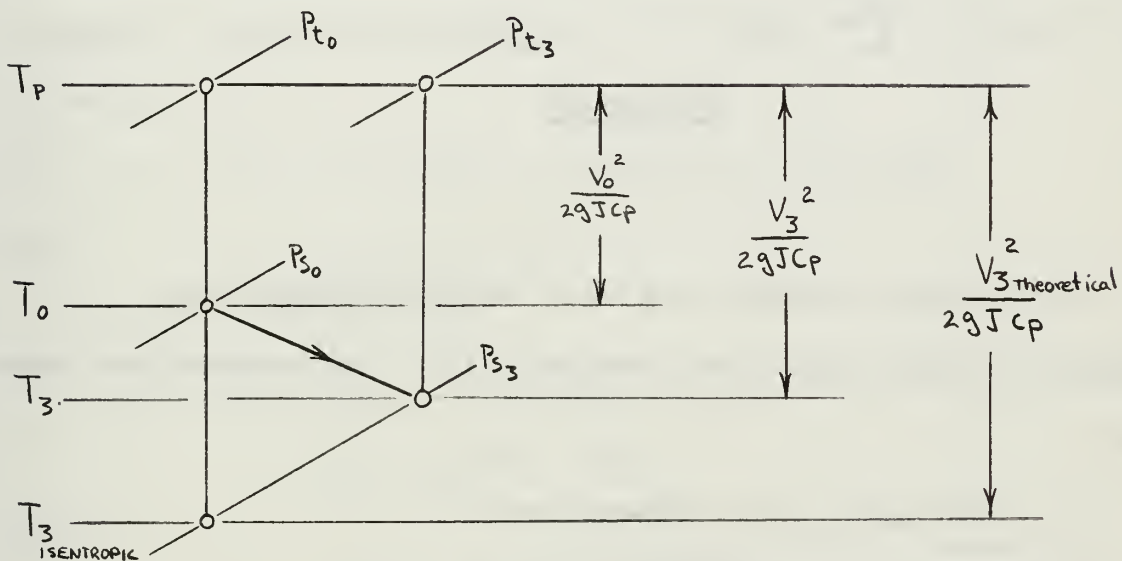
$$\zeta = \frac{V_{3\text{theor.}}^2}{V_3^2} - 1 \quad (19)$$

$$\frac{V_{3\text{theoret.}}^2}{2gJc_p} = T_p \left[1 - \left(\frac{P_{s3}}{P_{t0}} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

$$\frac{V_3^2}{2gJc_p} = T_p \left[1 - \left(\frac{P_{s3}}{P_{t3}} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

$$\zeta = \frac{1 - \left(\frac{P_{s3}}{P_{t0}}\right)^{\frac{\gamma-1}{\gamma}}}{1 - \left(\frac{P_{s3}}{P_{t3}}\right)^{\frac{\gamma-1}{\gamma}}} - 1 \quad (21)$$

For a turbine cascade,



$$\zeta = \frac{V_{3 \text{ theort.}}^2 - V_3^2}{V_3^2}$$

$$\zeta = \frac{V_{3\text{theoret.}}^2}{V_3^2} - 1$$

and, similar to Eq. (20),

$$\zeta = \frac{1 - \left(\frac{P_{s3}}{P_{t0}} \right)^{\frac{\gamma-1}{\gamma}}}{1 - \left(\frac{P_{s3}}{P_{t3}} \right)^{\frac{\gamma-1}{\gamma}}} - 1$$

Forces Acting on the Blades

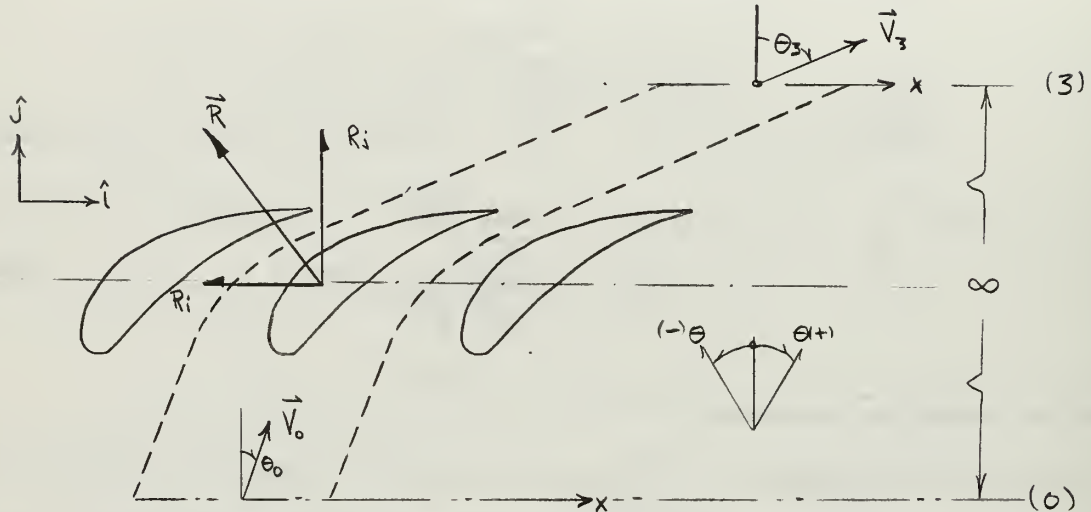


Figure A4

The control volume used will be that bounded by station (o) far ahead, and station (3). The assumptions made are:

- (a) The flow is two dimensional.
- (b) The flow is steady.

The Momentum equation (ignoring shear stress integrals)

gives

$$\int_{(0)} dm_s \vec{V}_0 - \int_{(3)} dm_s \vec{V}_3 + \hat{j} \int_{(0)} P_{s_0} dx - \hat{j} \int_{(3)} P_{s_3} dx = \vec{R} \quad (21)$$

and

$$\vec{V}_0 = \hat{i} V_0 \sin \theta_0 + \hat{j} V_0 \cos \theta_0$$

$$\vec{V}_3 = \hat{i} V_3 \sin \theta_3 + \hat{j} V_3 \cos \theta_3$$

The force acting on the blade per unit height and the axial direction is

$$R_j = \rho_0 V_0^2 \cos^2 \theta_0 \Delta X - \rho_3 V_3^2 \cos^2 \theta_3 \Delta X + P_{s_0} \Delta X - P_{s_3} \Delta X \quad (22)$$

for uniform flow conditions at station (0) and (3). The

force per unit height acting on the blade in the tangential direction is

$$R_i = \frac{1}{2} \rho_0 V_0^2 \sin 2\theta_0 \Delta X - \frac{1}{2} \rho_3 V_3^2 \sin 2\theta_3 \Delta X \quad (23)$$

and

$$|\vec{R}| = \sqrt{R_i^2 + R_j^2}$$

The mean vectorial velocity is

$$\vec{V}_\infty = \frac{1}{2} (\vec{V}_0 + \vec{V}_3)$$

or

$$V_\infty = \frac{1}{2} \sqrt{[V_0 \sin \theta_0 + V_3 \sin \theta_3]^2 + [V_0 \cos \theta_0 + V_3 \cos \theta_3]^2} \quad (24)$$

where \vec{V}_∞ is as shown in Fig. A5.

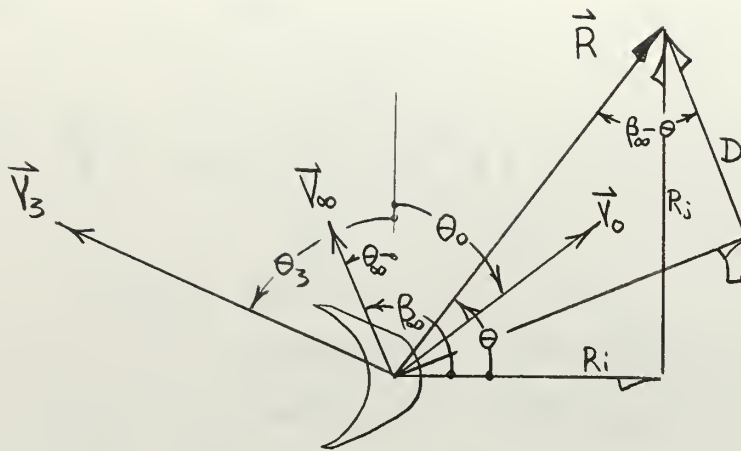


Figure A5

Also

$$\theta_{\infty} = \arctan \frac{[V_0 \cos \theta_0 + V_3 \cos \theta_3]}{[V_0 \sin \theta_0 + V_3 \sin \theta_3]} \quad (25)$$

The drag force then is that component of \vec{R} which is parallel to \vec{V}_{∞} and the lift force is that component of \vec{R}

perpendicular to \vec{V}_{∞} . Then,

$$\vec{R} = \vec{L} + \vec{D}$$

$$L = R \sin(\beta_{\infty} - \theta)$$

$$D = R \cos(\beta_{\infty} - \theta)$$

where L , and D are the lift and drag force per unit height acting on the blade.

The lift and drag coefficients are defined as

$$C_L = \frac{L}{\frac{1}{2} \rho V_{\infty}^2 c} \quad (26)$$

and

$$C_D = \frac{D}{\frac{1}{2} \rho V_o^2 c} \quad (27)$$

where c is the blade chord and

$$\rho = \frac{1}{2} [\rho_o + \rho_3]$$

The lift and drag coefficients may also be defined as [8]

$$C_{L_o} = \frac{L}{\frac{1}{2} \rho_o V_o^2 c}$$

and

$$C_{D_o} = \frac{D}{\frac{1}{2} \rho_o V_o^2 c}$$

APPENDIX B

PROGRAM CASCADE

The data reduction computer program, entitled CASCADE, utilizes FORTRAN 60. Program CASCADE reads in the measured data of a cascade test in the form of input data cards, utilizes the equations developed in Appendix A, and displays the results in printed and graphical form. Output from CASCADE includes the following:

1. Conditions far ahead of the cascade
 - a. V_0 (ft./sec.)
 - b. α_0 (deg.)
 - c. P_{t0} (lbs./sq.ft.)
 - d. P_{s0} ((lbs./sq.ft.)
2. Conditions far aft of the cascade
 - a. V_3 (ft./sec.)
 - b. α_3 (deg.)
 - c. P_{t3} (lbs./sq.ft.)
 - d. P_{s3} (lbs./sq.ft.)
3. Average conditions at the measuring planes
 - a. P_{t1} (lbs./sq.ft.)
 - b. P_{s1} (lbs./sq.ft.)
 - c. P_{t2} (lbs./sq.ft.)
 - d. P_{s2} (lbs./sq.ft.)

4. Forces on the blades models (lbs. per ft.)
 - a. Axial force
 - b. Tangential force
 - c. Lift
 - d. Drag
5. Total turning angle of the flow (deg.).
6. Dimensionless loss coefficient of Eq. (20) between station (0) and station (3) which includes the mixing losses.
7. Lift and Drag coefficients based on the vectorial mean of V_0 and V_3 (i.e., V_∞); (dimensionless).
8. Lift and Drag coefficients based on V_0 ; (dimensionless).
9. Constriction factor; equal to

$$\frac{\int_{(1)} \rho_1 V_1 \cos \theta_1 dx}{\int_{(2)} \rho_2 V_2 \cos \theta_2 dx} \quad (\text{dimensionless})$$
10. Total distance traversed, Δx for both upper and lower traverse (in.).
11. Density far ahead and far aft (slugs/cu.ft.).
12. Reynold's number based on blade chord and V_3 ; (dimensionless).
13. Mach number based on V_0 for the rotor cascade and V_3 for the stator cascade. (dimensionless).

FORTRAN Symbols

Symbols which are followed by an L to indicate association with the lower traverse or a U to indicate association with the upper traverse are as follows:

<u>FORTRAN Symbol</u>	<u>Definition</u>
X	x
DX	Δx
PS	P _s
PT	P _t
DP	ρ
THETA	θ
TX	Total distance traversed
PCM	Probe Mach number correction factor
PCP	Probe pitch angle correction correction

Symbols which are followed by an A for station(o) or a B for station(3) are:

<u>FORTRAN Symbol</u>	<u>Definition</u>
PT	P _t
PS	P _s
DELP	P _t - P _s
THETA	θ
RHO	ρ
V	V

VCT $V \cos \theta$

VST $V \sin \theta$

Symbols which are followed by a 1 for station(1) (lower traverse) or a 2 for station(2) (upper traverse) are:

<u>FORTRAN Symbol</u>	<u>Definition</u>
PT	Average total pressure
PS	Average static pressure
RHO	ρ

Symbols associated with the various integrals involved are:

<u>FORTRAN Symbol</u>	<u>Definition</u>
CC1	$\int \rho_1 V_1 \cos \theta_1 dx$
EE1	$\int \rho_1 dx$
FFA	$\int P_{s1} V_1 \cos \theta_1 dx$
FF1	$\int P_{t1} V_1 \cos \theta_1 dx$
GG1	$\int V_1 \cos \theta_1 dx$
HH1	$\int V_1 dx$
TT1	$\int \theta_1 dx$
AA2	$\int P_{s2} dx$
BB2	$\int \rho_2 V_2^2 \cos \theta_2 dx$

FORTRAN SymbolDefinition

CC2	$\int \rho_2 V_2 \cos \theta_2 dx$
DD2	$\int \rho_2 V_2^2 \sin 2\theta_2 dx$
EE2	$\int \rho_2 dx$
FFB	$\int P_{s2} V_2 \cos \theta_2 dx$
FF2	$\int P_{t2} V_2 \cos \theta_2 dx$
GG2	$\int V_2 \cos \theta_2 dx$

Symbols used without suffix:

FORTRAN SymbolDefinition

A	Conversion unit; 5.2022 (lb./ft. ²)/(in. H ₂ O)
AP2	$\gamma g R T_p$
AP3	$\frac{\gamma-1}{\gamma}$
BETAIN	β_∞
BN	Number of blade spacings traversed
BP	P atm
B	$1 - \frac{2V_3^2}{\gamma g R T_p}$

FORTTRAN SymbolDefinition

C	Chord
CD	Coefficient of drag based on V_∞ and ρH_0
CL	Coefficient of lift based on V_∞ and ρH_0
CD1	Coefficient of drag based on V_0 and ρ_0
CL1	Coefficient of lift based on V_0 and ρ_0
CB	$\left[1 - \frac{q_3}{p_{t_3}} \right]^{1/\gamma}$
DR	$ \vec{R} $
DRA	R_j
DRU	R_i
DELB	$\theta_0 - \theta_3$
DRAG	Drag
DRHO	$\Delta \rho$
G	g
GAMMA	γ

FORTTRAN SymbolDefinition

K	Run number
L	Number of lower data points
M	Number of upper data points
MO	Mach number
PSI	$\frac{\int_{(1)} \rho_1 V_1 \cos \theta_1 dx}{\int_{(2)} \rho_2 V_2 \cos \theta_2 dx}$
R	R . g
REO	Reynolds Number
RHO	$\frac{1}{2} [\rho_0 + \rho_3]$
RHOBC	$\frac{\gamma P_{t3}}{\gamma g R T_P} \left[1 - \frac{q_3}{P_{t3}} \right]^{\frac{1}{\gamma}}$
S	Blade spacing
SIGMA	Solidity = c/s
STAN	Stagger angle
TA	Tp (°R)
TF	Tp (°F)
TA	T ₃ (°R)

<u>FORTRAN Symbol</u>	<u>Definition</u>
T1	T_0 ($^{\circ}\text{R}$)
TLIFT	Lift
THETA1N	θ_{∞}
VA ²	V_0^2
VB ²	V_3^2
VIN	V_{∞}
VISC	μ

The statements in program CASCADE are indexed by a six-digit number which appears at the extreme right of the program printout (see Table C1); i.e., in columns 74 to 80 of the IBM card format. In referring to these indices, all zeros will be neglected. For instance, index number 101 will appear in the program printout as 001010. In other words, the statements are numbered consecutively within digits three through five of the six-digit index. Reference to statement numbers will mean the numbers which appear in columns one through six of the IBM card format.

Statements 0 through 12 establish the arrays used in the program arithmetic and provide for the graph output titles in accordance with subroutine draw of the FORTRAN 60 library

(associated with the CDC 1604 computer). The COMMON statement is required (index #5) since the memory cells reserved by CASCADE in conjunction with subroutine DRAW exceed the present memory capacity of the CDC 1604 system.

Statements 13 through 18 read the input data into the computer. Data input for CASCADE is in the form of data cards. A set of data consists of the following:

- (a) First subset: A single card reads in: Run number, Barometric pressure, Plenum temperature, number of blade spacings traversed, the blade spacing.
- (b) Second subset: A single card with one number reads in: the total number data points to be read in for the lower traverse data.
- (c) Third subset: The set of lower traverse data points: one card per point. The total number of cards in the set must be equal to the number appearing in (b), the second subset.
- (d) Fourth subset: A single card with one number: the total number of data points to be read in for the upper traverse data.
- (e) Fifth subset: A single card reads in: the blade chord, the stagger angle of the cascade, the pitch angle and Mach number correction factors for the lower and upper YC-120 probes, respectively.

Input data must have the following dimensions:

- (a) Temperature: °F
- (b) Barometric pressure: in. of Hg
- (c) All other pressures: in. of H₂O
- (d) Angles: deg.
- (e) Lengths: inches
- (f) All other data: non-dimensional

After input data is read in, statements indexed 21 through 40, by means of a sequence of individual DO LOOPS, establish the following data for both upper and lower traverses.

- (a) Total distance traversed.
- (b) The x coordinate of the individual data points with the first point assigned $x = 0$.
- (c) The static pressure at each point.

Subroutine DRAW is summoned by statements 41 through 52 with the appropriate graph label preceding each call statement. The statements for draw exhibited in Table C1 are of the format which allows automatic scale factor adjustment by the CDC 1604. Statements 53 through 58 print out the input data. The graphical and printed output are in the dimensions of the input data (i.e., in. of H₂O, inches, etc.)

Statements 59 through 90 establish constants, correct static pressure readings for probe calibrations in accordance

with equations established by United Sensor and Control Corporation calibration charts, and converts pressures, temperatures, angles, and lengths to the units used in computations. The converted units are:

- (a) Pressures: lbs./sq.ft., absolute
- (b) Temperature: °R
- (c) Length: ft.
- (d) Angles: radians

Using the thermodynamic relations of Appendix A, densities and velocities are computed for each probe position by means of statements 91 through 100. Statements 101 through 150 perform the summation approximations to the various integrals. The form of the integration is:

$$\int f(x) dx \cong \sum_{i=1}^n [f(x_i) + f(x_{i+1})] \frac{1}{2} (x_{i+1} - x_i)$$

The method of determining the mass density of the mixed flow far aft of the cascade given in Appendix A is programmed in statements 151 through 172. In the process of the iteration for density at station (3), the pressures, velocity and flow angle at (3) are also established. Statements 173 through 182 compute flow properties far ahead of the cascade based on the previously computed integrals. In addition, the average pressures at the measuring planes are established.

Statements 183 through 233 compute the remaining output information, namely:

- (a) Forces on the blades
- (b) Constriction factor
- (c) Lift and Drag coefficients
- (d) Total turning angle of the flow
- (e) Mach and Reynold's numbers
- (f) Loss coefficient

The remaining statements through index number 312 are the PRINT and FORMAT statements for the computed output.

Program CASCADE is designed to process more than one set of input data. Statement index number 313 just before STOP starts the computing process at statement number 1; the READ statements. If there is only one set of data, the program will exit the loop normally and stop. If there is more than one set of data, the program will read in the next set. CASCADE will work for both compressor or turbine cascade data. The only difference between the two is the computation of lift and drag from the axial and tangential blade force components, because of possible differences in sign of the leaving flow angle. This is handled by the IF statement index number 197. If multiple sets of input data are used, graphs will be plotted for each set, however, the graph title will not change.

Table B1

PROGRAM LISTING

```

..JOB0322F BARTOCCI
PROGRAM CASCADE
DIMENSION XL(900),XU(900),DPL(900),DPU(900),THETAL(900),THETAU(900
1),PTL(900),PTU(900),PSL(900),PCU(900),RHO1(900),RHO2(900),IN(10),
2DXL(900),DXU(900),ITITLE(12),VL2(900),VU2(900)
COMMON XL,XU,DPL,DPU,THETAL,THETAU
DO 1850 I=1,12
1850 ITITLE(I)=84
ITITLE(1)=8HRUN 304
ITITLE(3)=84 ROTOR
ITITLE(4)=8HPROFILES
ITITLE(6)=8HBARTOCCI
1 READ 801,K,RP,TF,BN,S
READ 2,L
READ 803,(IL,DXL(I),THETAL(I),DPL(I),PTL(I),I=1,L)
READ 2,M
READ 803,(IU,DXU(I),THETAU(I),DPU(I),PTU(I),I=1,M)
READ 3,C,STAN,PCPL,PCVL,PCPU,PCWU
2 FORMAT (I3)
3 FORMAT(6F10.2)
TXL=0.0
DO 150 I=2,L
TXL=TXL+DXL(I)
150 CONTINUE
TXU=0.0
DO 151 I=2,M
TXU=TXU+DXU(I)
151 CONTINUE
XL(1)=0.0
PSL(1)=PTL(1)-DPL(1)
DO 1800 I=2,L
XL(I)=XL(I-1)+DXL(I)
PSL(I)=PTL(I)-DPL(I)

```



```

S=5/12.
TXL=TXL/12.
TXU=TXU/12.
DO 125 I=1,L
DXL(I)=DXL(I)/12.
THETAL(I)=THETAL(I)/57.2958
PSL(I)=PSL(I)*A+BP
PTL(I)=PTL(I)*A+BP
PSL(I)=(PSL(I)-PCPL*PTL(I))/(1.-PCPL)
PSL(I)=(PSL(I)-PCVL*PTL(I))/(1.-PCVL)
DPL(I)=PTL(I)-PSL(I)
125 CONTINUE
DO 100 I=1,M
DXU(I)=DXU(I)/12.
PTU(I)=PTU(I)*A+BP
PSU(I)=PSU(I)*A+BP
PSU(I)=(PSU(I)-PCPU*PTU(I))/(1.-PCPU)
PSU(I)=(PSU(I)-PCMU*PTU(I))/(1.-PCMU)
DPU(I)=PTU(I)-PSU(I)
THETAU(I)=THETAU(I)/57.2958
100 CONTINUE
C
THE FOLLOWING STATEMENTS COMPUTE THE VARIOUS INTEGRALS
DO 121 I=1,L
RHO1(I)=(GAMMA-(DPL(I)/PTL(I))-(AP3*DPPL(I)*DPL(I))/(PTL(I)**2))
1*PTL(I)/AP2
VL2(I)=2.*AP2*DPPL(I)/PTL(I)*(1.+DPL(I)/(PTL(I)*2.*GAMMA))/1.4
121 CONTINUE
DO 122 I=1,M
RHO2(I)=(GAMMA-(DPU(I)/PTU(I))-(AP3*DPU(I)*DPU(I))/(PTU(I)**2))
1*PTU(I)/AP2
VU2(I)=2.*AP2*DPU(I)/PTU(I)*(1.+DPU(I)/(PTU(I)*2.*GAMMA))/1.4
122 CONTINUE
LL=L-1
CC1=0.0
FF1=0.0
FFA=0.0

```



```

FF1=0.0
GG1=0.0
HH1=0.0
TT1=0.0
DO 200 I=1,LL
  RP=RHO1(I)*SQRTF(VL2(I))
  QR1=RH01(I+1)*SQRTF(VL2(I+1))
  CCI=CCI1+(RR*COSF(THETAL(I))+RRP1*COSF(THETAL(I+1)))*DXL(I+1)*.5
  EE1=EE1+(RH01(I)+RH01(I+1))*DXL(I+1)*.5
  FF1=FF1+(PTL(I)*SQRTF(VL2(I))*COSF(THETAL(I))+PTL(I+1)*SQRTF(VL2(I+1))*COSF(THETAL(I+1)))*DXL(I+1)*.5
  GG1=GG1+(SQRTF(VL2(I))*COSF(THETAL(I))+SQRTF(VL2(I+1))*COSF(THETAL(I+1)))*DXL(I+1)*.5
  HH1=HH1+(VL2(I)+VL2(I+1))*DXL(I+1)*.5
  TT1=TT1+(THETAL(I)+THETAL(I+1))*DXL(I+1)*.5
200 CONTINUE
MM=M-1
AA2=0.0
BP2=0.0
CC2=0.0
DD2=0.0
EE2=0.0
FF2=0.0
GG2=0.0
DO 300 I=1,MM
  AA2=AA2+(PSU(I)+PSU(I+1))*DXU(I+1)*.5
  THU=COSF(THETAU(I))*2
  THUU=COSF(THETAU(I+1))*2
  BB2=BB2+(RH02(I)*VU2(I)+THU+RH02(I+1)*VU2(I+1))*DXU(I+1)*.5
  RR2=RH02(I)*SQRTF(VU2(I))
  RR3=RH02(I+1)*SQRTF(VU2(I+1))
  CC2=CC2+(RR2*COSF(THETAU(I))+RR3*COSF(THETAU(I+1)))*DXU(I+1)*.5
  DD2=DD2+((-H02(I)*VU2(I)*SINF(2.*THETAU(I))+RH02(I+1)*VU2(I+1))*SINF

```



```

1(2.*THETAU(I+1))*DXU(I+1)*.5
EE2=EE2+(RHO2(I)+RHO2(I+1))*DXU(I+1)*.5
FF2=FF2+(PTU(I)*SQRTF(VU2(I))*COSF(THETAU(I))+PTU(I+1)*SQRTF(VU2(I
+1))*COSF(THETAU(I+1))*DXU(I+1)*.5
GG2=GG2+(SQRTF(VU2(I))*COSF(THETAU(I)) +SQRTF(VU2(I+1))*COSF(THET
IAU(I+1))*DXU(I+1)*.5
FFB=FFB+(PSU(I)*SQRTF(VU2(I))*COSF(THETAU(I))+PSU(I+1)*SQRTF(VU2(I
+1))*COSF(THETAU(I+1))*DXU(I+1)*.5
300 CONTINUE
C ITERATION TO DETERMINE THE DENSITY FAR AHEAD AND FAR AFT OF THE
C CASCADE.
TOL=.000001
DPHO=.0000001
EX=1./1.4
RHOA=EE1/IXL
RHOP=.001
202 PSB=(AA2/TXU)+ RB2/TXU -((CC2**2)/(RHOB*TXU*TXU))
306 VB2=.25*((DD2**2)/(CC2*CC2))+((CC2**2)/(RHOB*RHOB*TXU*TXU))
VR=SQRTF(VB2)
THETA=ATANF(RHOB*TXU*DD2/(2.*CC2**2))
B=1.-.2*VR2/AP2
PB=PB**2.5
PTR=PSB/PB
DELPA=PTR-PSE
CR=(1.-DELPA/PTR)**EX
RHOBC=1.4*PB*CR/AP2
ERR=ABSF(RHOB-RHOBC)
IF(ERR-ICL) 302,302,304
304 RHOB=RHOB+DRHO
GO TO 306
302 CONTINUE
C DETERMINATION OF FORCES ACTING ON THE BLADES IN CASCADE
PT1=FF1/GG1
PS1=FFA/GG1
PT2=FF2/GG2
PS2=FFB/GG2

```

```

001420
001430
001440
001450
001460
001470
001480
001490
001500
001510
001520
001530
001540
001550
001560
001570
001580
001590
001600
001610
001620
001630
001640
001650
001660
001670
001680
001690
001700
001710
001720
001730
001740
001750
001760
001770

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```

PTA=PT11
PSA=PS1
THETA=TT1/TXL
VA2=HH1/TXL
VA=SQRTF(VA2)
PSI=CC1/CC2
VSTA=VA*SINF(THETA)
VCTA=VA*COSE(THETA)
VSTB=VB*SINF(THETA)
VCTB=VB*COSE(THETA)
S=4./12.
DRA=S*(RHOA*VCTA-RHOB*VCTR*VCTB)+(PSA-PSB)*S
DRU=.5*S*(RHOA*VA2*SINF(2.*THETA)-RHOB*VB2*SINF(2.*THETA))
VIN=SQRTF(.25*(VSTA+VSTB)*(VSTA+VSTB)+.25*(VCTA+VCTB)*(VCTA+VCTB))
THETA=ATANF((VSTA+VSTB)/(VCTA+VCTB))
BETA=3.14159/2.-THETA
TB=TA-VB2*.4/(2.*778.28*GAMMA*R)
TI=TA-VA2*.4/(2.*778.28*GAMMA*R)
IF(THETA) 500,500,501
THETA=ATANF(DRA/DRU)
THETA=ABSF(THETA)
DR=SQRTF(DRA*DR4+DRU*DRU)
DPAG=DP*COSE(BETA-THETA)
TLIFT=DR*SINF(BETA-THETA)
AMO=VA/SQRTF(GAMMA*R*TI)
GO TO 502
501 THETA=ATANF(DRU/DRA)
THETA=ABSF(THETA)
TLIFT=DR*COSE(BETA-THETA)
DRAG=DR*SINF(BETA-THETA)
AMO=VR/SQRTF(GAMMA*R*TB)
GO TO 502
502 C=C/12.
PHO=.5*(RHOA+RHOB)
CL=2.*TLIFT/(RHO*C*VIN*VIN)
DPB=PTB-PSB
001780
001790
001800
001810
001820
001830
001840
001850
001860
001870
001880
001890
001900
001910
001920
001930
001940
001950
001960
001970
001980
001990
002000
002010
002020
002030
002040
002050
002060
002070
002080
002090
002100
002110
002120
002130

```

```

CON=(1.-PSB/PTA)/(2.*GAMMA)
CONS=DPB/(2.*GAMMA*PTB)
ZETA=((PTB*(PTA-PSB)*(1.-CON))/(PTA*DPB*(1.-CONS)))-1.
CD=2.*DRAG/(RHO*C*VIN*VIN)
CL1=CL*RHO*VIN*VIN/(RHOA*VA2)
CD1=CD*RHO*VIN*VIN/(RHOA*VA2)
THETA=THETA*57.3
THETA3=THETA*57.3
THETA1N=THETA*57.3
THETA=THETA*57.3
RETA1N=RETA*57.3
CONVERT RP(LB/SQ FT) TO IN. HG.
RP=RP/70.727
TXL=TXL*12.
TXU=TXU*12.
SIGMA=C/S
VISC=0.0001*(TB/400.)*.76
VISC=VISC*.031081
RHO=VISC*CPHOB/VISC
DELTA=THETA-THETA3
800 FORMAT(8H10IN NO. 5X 2HRP 5X 4HTFAD 5X 2HRM 5X 1HS / )
801 FORMAT ( 15, F11.2, F8.1, F7.0, F7.1)
802 FORMAT(6HOPPOINT6X2HXL3X6HTHETAL5X3HDPL7X3HPTL7X3HPSL / )
803 FORMAT(16,F14.5,3F10.4)
804 FORMAT(6HOPPOINT6X2HXL3X6HTHETA15X3HDPU7X3HPTU7X3HPDU / )
805 FORMAT(15,5F10.2)
910 FORMAT ( 6HICL1 = F10.5, 5X 5HCD1 = F10.5 )
      PRINT 400
400 FORMAT(1H1//32X21HPROPULSION LABORATORY/28X30HU.S. NAVAL POSTGRADU
      IATE SCHOOL//)
      PRINT 401,K
401 FORMAT(35X13HTEST RUN NO. 13//)
      PRINT 402,BP
402 FORMAT(27X20HBAROMETRIC PRESS. = F6.2,8H IN. HG.//)
      PRINT 403,TF
403 FORMAT(29X16H PLENUM TEMP. = F4.1,8H DEG. F.//)

```

```

404 PRINT 404,STAN                                002500
404 FORMAT(29X16HSTAGGER ANGLE = F5.2,4HDEG.//)    002510
405 PRINT 405,SIGMA                                002520
405 FORMAT(33X11HSOLIDITY = F4.2//)                002530
406 PRINT 406                                        002540
406 FORMAT(28X16HBLADE PROFILE = //)              002550
407 PRINT 407                                        002560
407 FORMAT(10X22HFAIR AHEAD (STATION 0 )11X22HFAIR AFT (STATION 3 )//) 002570
408 PRINT 408                                        002580
408 FORMAT(8X2HV03X8HALPHA 0 2X3HPT04X3HPS010X2HV33X8HALPHA 3 2X3HPT34 002590
1X2HPS3)
409 PRINT 409                                        002600
409 FORMAT(5X29H(FT/SEC) (DEG) (PSF) 5X29H(FT/SEC) (DEG) (PS 002610
IF) (PSF)//)
410 PRINT 410,VA,THETA4,PT4,PS4,VB,THETA3,PT3,PS3 002620
410 FORMAT(5XF8.3,F7.2,2F8.1,F12.3,F7.2,2F8.1//) 002630
411 PRINT 411                                        002640
411 FORMAT(21X34HCONDITIONS AT THE MEASURING PLANES//) 002650
412 PRINT 412                                        002660
412 FORMAT(0X27HLOWER TRAVERSE (STATION 1 )5X27HUPPER TRAVERSE (STATIO 002670
IN 2 )//)
413 PRINT 413                                        002680
413 FORMAT(14X3HPT19X3HPS117X3HPT20X3HPS2) 002690
414 PRINT 414                                        002700
414 FORMAT(13X5H(PSF)7X5H(PSF)15X5H(PSF)7X5H(PSF)//) 002710
415 PRINT 415,PT1,PS1,PT2,PS2 002720
415 FORMAT(5X2F12.1,5X2F12.1//) 002730
416 PRINT 416                                        002740
416 FORMAT(21X36HFORCES ON THE BLADES IN LBS. PER FT.//23X5HAXIAL2X10H 002750
1TANGENTIAL3X4HLIFT4X4HDPAG//)
417 PRINT 417,DPA,DRU,TLIFT,DRAG 002760
417 FORMAT(21XF7.2,2F10.2,5F.2//) 002770
418 PRINT 418,DELB 002780
418 FORMAT(15X4CHTOTAL TURNING ANGLE OF THE FLOW (DEG) = F6.2//) 002790
419 PRINT 419,K 002800
419 FORMAT(1H1//10HRUN NO. = I3,10H CONCLUDED///// 002810
002820
002830
002840
002850

```



```

002860      PRINT 420,ZETA
002870      420 FORMAT(10X42HLOSS COEFFICIENT , MIXING LOSS INCLUDED = F8.5///)
002880      PRINT 422
002890      422 FORMAT(22X35HLIFT AND DRAG COEFFICIENTS BASED ON/22X31HTHE VECTORI
002900      1AL MEAN OF V0 AND V3//27X2HCL16X2HCD//)
002910      PRINT 423,CL,CD
002920      423 FORMAT(14X2F17.4//)
002930      PRINT 424
002940      424 FORMAT(22X35HLIFT AND DRAG COEFFICIENTS BASED ON/22X35HCONDITIONS
002950      1FEAR AHEAD OF THE CASCADE//27X3HCL015X3HCD//)
002960      PRINT 425,CL1,CD1
002970      425 FORMAT(14X2F17.4//)
002980      PRINT 426,PSI
002990      426 FORMAT(20X38HCONSTRICTION FACTOR.
003000      = F6.4//)
003010      PRINT 427,TXL
003020      427 FORMAT(20X38HDELTA X LOWER
003030      = F6.2//)
003040      PRINT 428,TXU
003050      428 FORMAT(20X38HDELTA X UPPER
003060      = F6.2//)
003070      PRINT 429,DHCA
003080      429 FORMAT(20X38HREYNOLDS NUMBER(CHORD) AND MACH NUMBER/24X4H REY14X3H
003090      1 NO//)
003100      PRINT 430,REO,AMQ
003110      430 FORMAT(17X15.0,F15.4)
003120      GO TO 1
003130      STOP
003140      END
003150      END
003160

```


APPENDIX C RESULTS OF THE CASCADE TESTS

Table C1

PROPULSION LABORATORY
U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 300

BAROMETRIC PRESS. = 30.19 IN. HG.

PLENUM TEMP. = 69.0 DEG. F.

STAGGER ANGLE = 68.00DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)				FAR AFT (STATION 3)			
V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
76.407	.29	2272.2	2264.9	356.496	78.45	2264.6	2110.1

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)		UPPER TRAVERSE (STATION 2)	
PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2272.2	2264.9	2264.8	2109.9

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAW
52.47	-19.69	56.00	2.30

TOTAL TURNING ANGLE OF THE FLOW (DEG) = -78.16

RUN NO. = 300 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .04437

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V0 AND V3

CL

CD

2.3005

.0943

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0

CD0

13.8368

.5674

CONSTRICION FACTOR = 1.1268

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00249808

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00237160

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
BASED ON VIN

REY

MO

1221047.

.3162

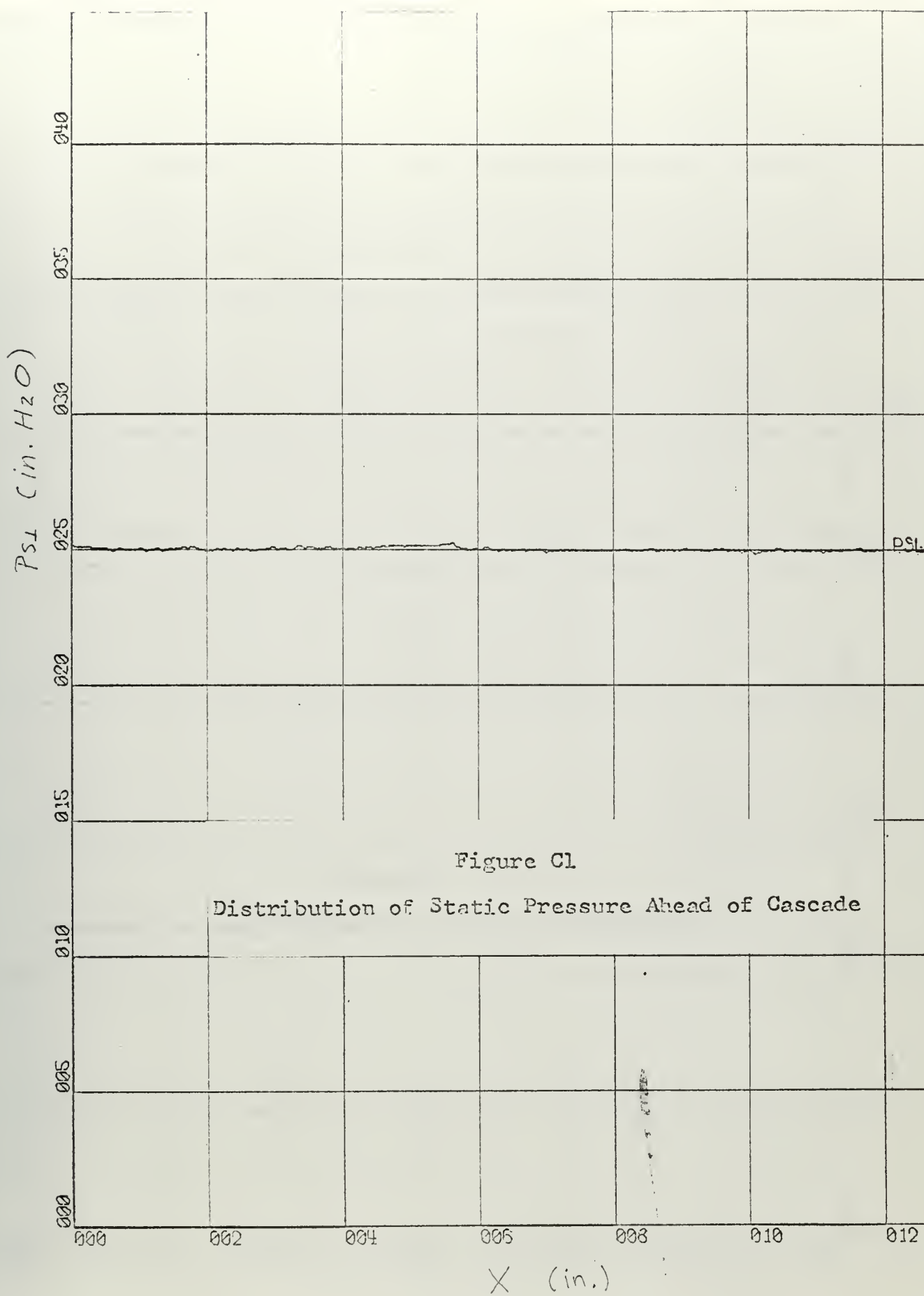


Figure C1

Distribution of Static Pressure Ahead of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 300

STATOR PROFILES

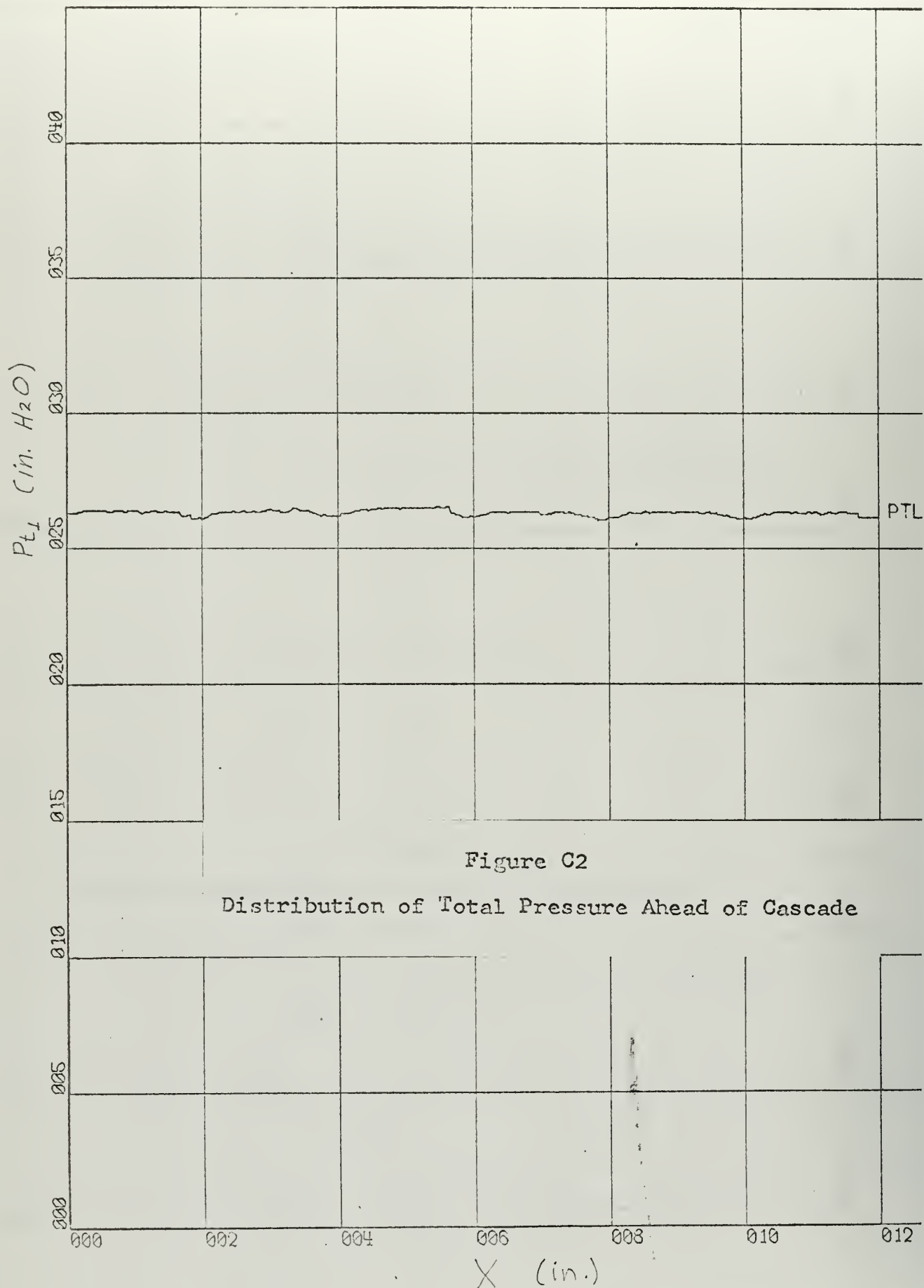


Figure C2

Distribution of Total Pressure Ahead of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RIIN 300

STATOR PROFILES

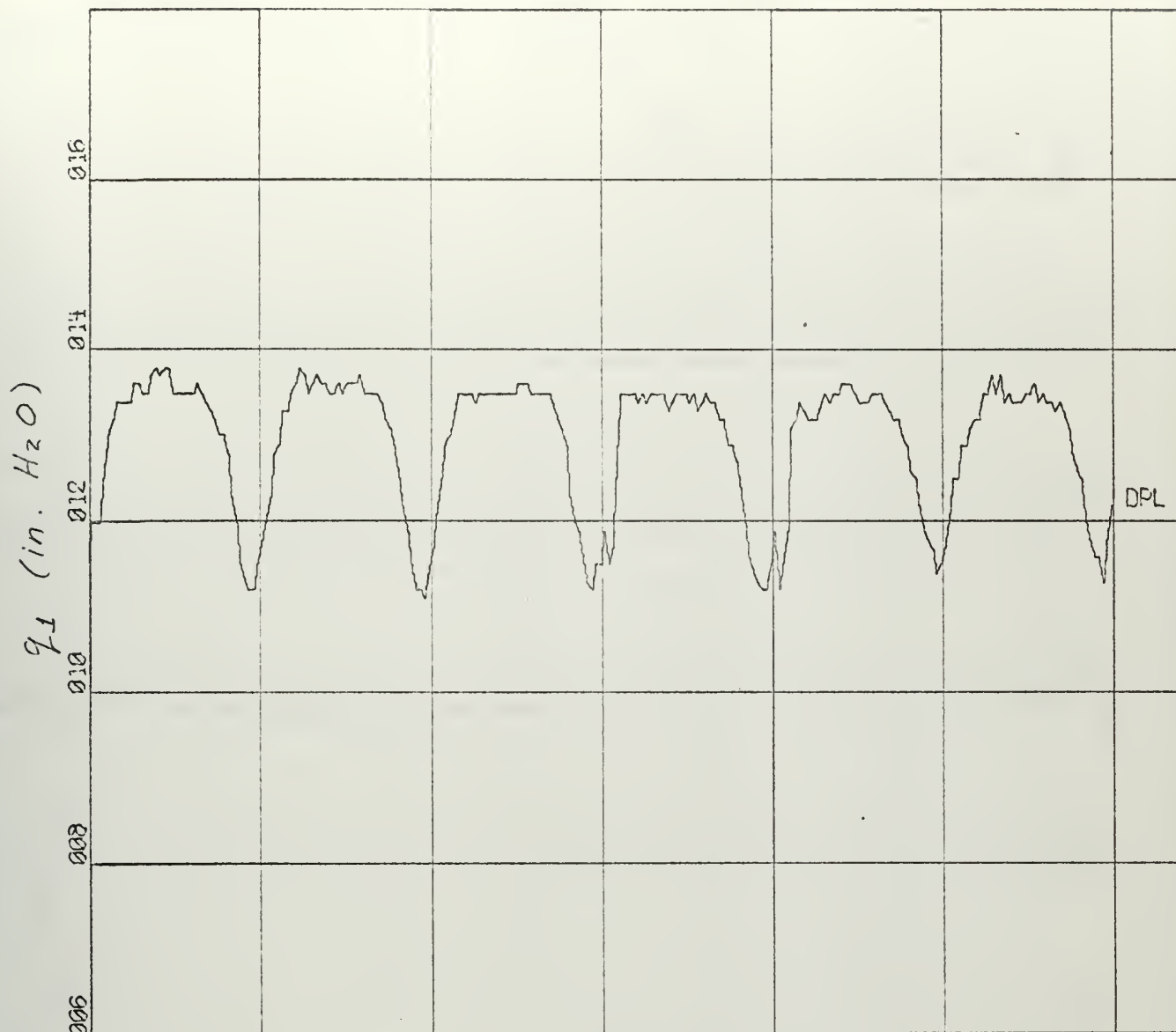
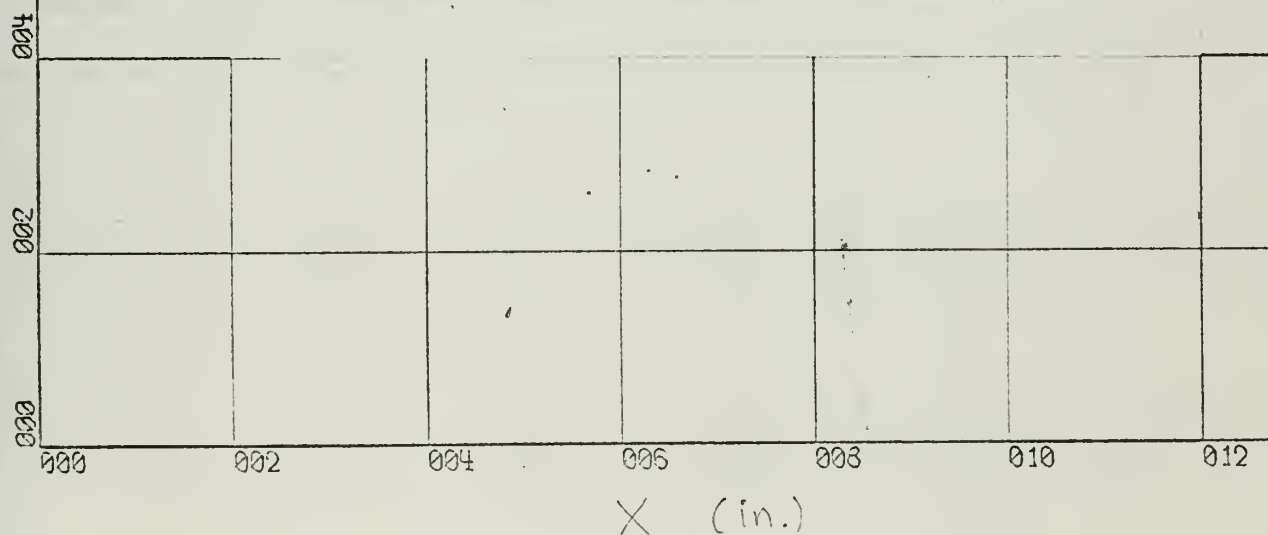


Figure C3

Distribution of Dynamic Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E-01 UNITS/INCH.

RUN 300

STATOR PROFILES

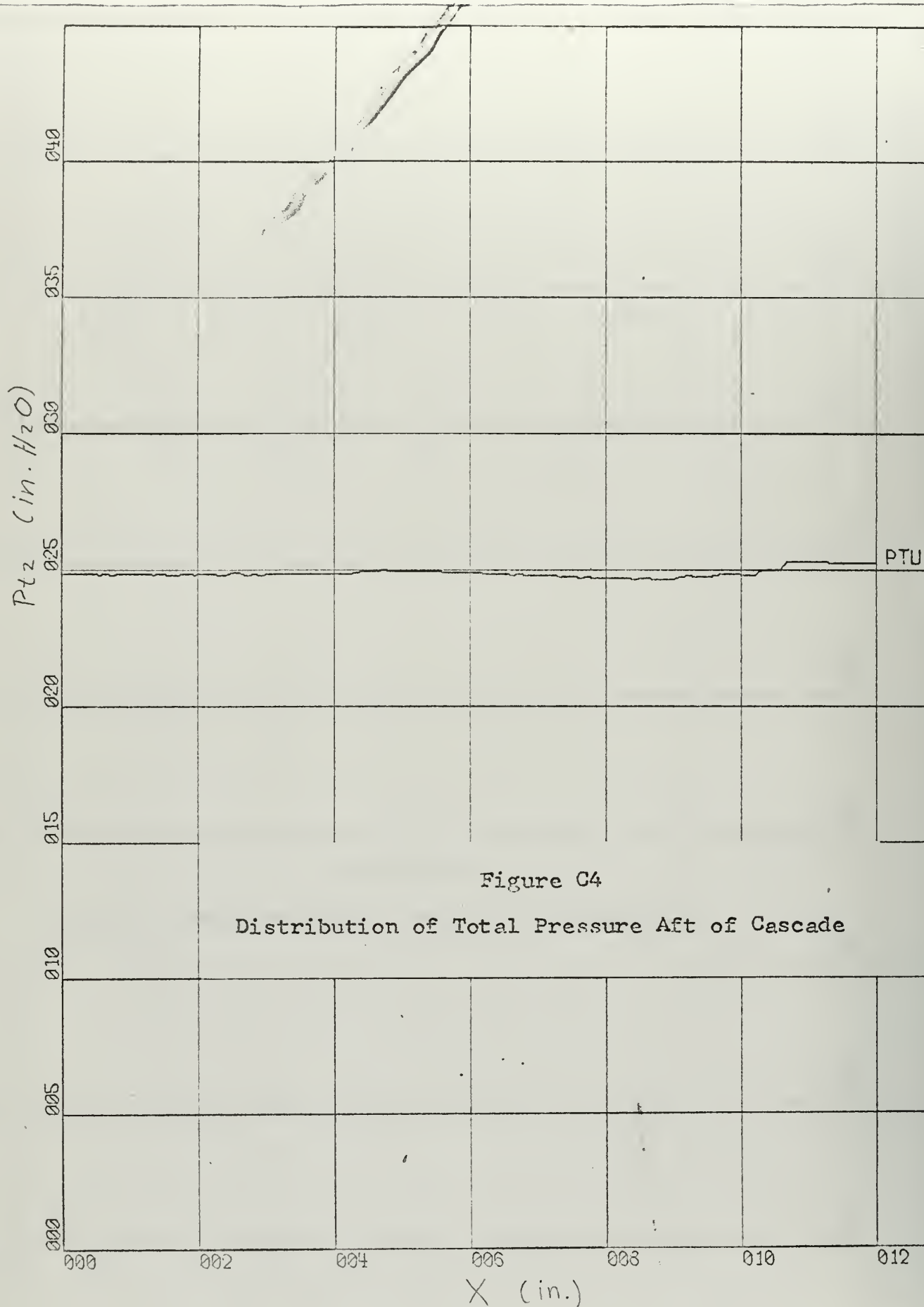


Figure C4

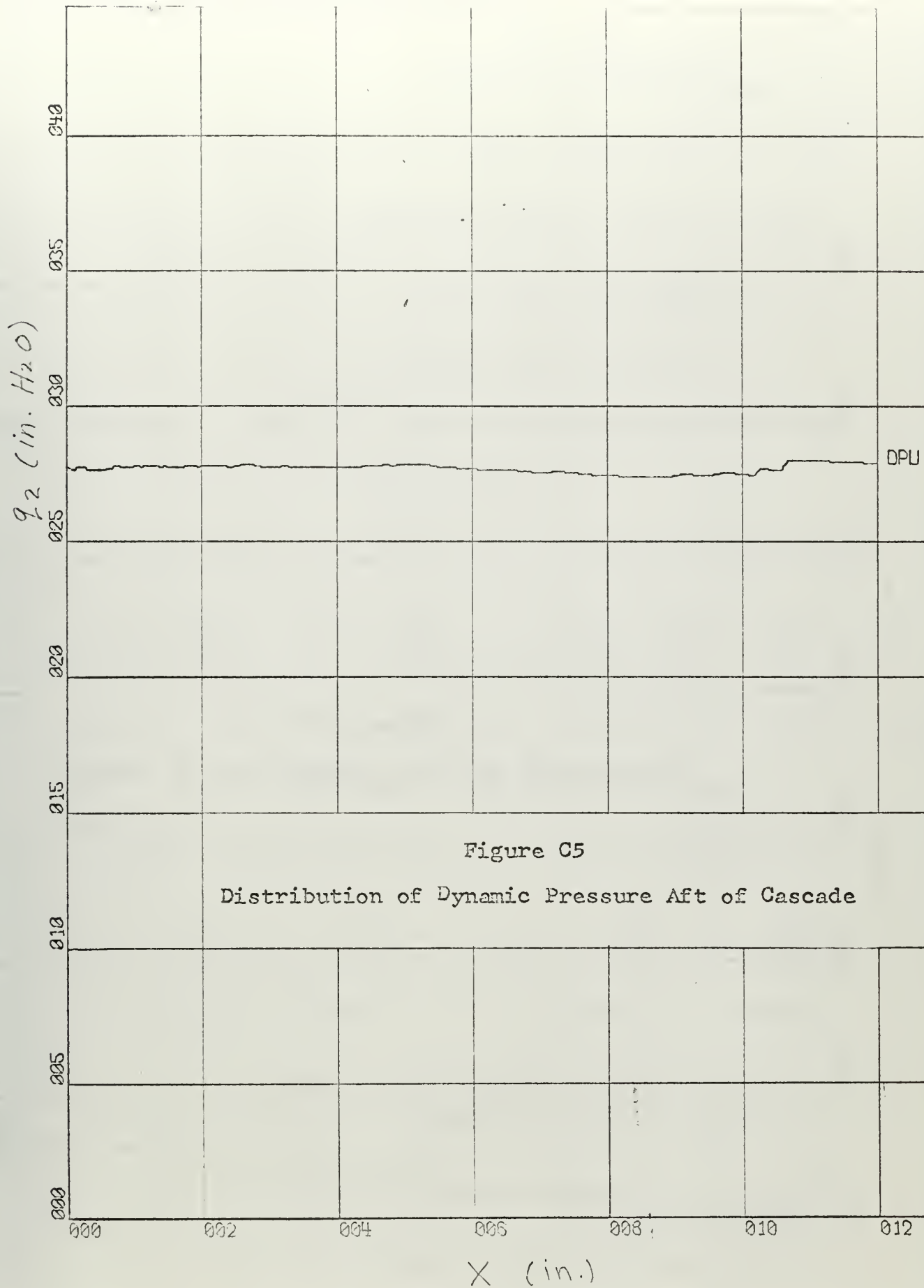
Distribution of Total Pressure Aft of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RI. IN. 300

STATOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 300

STATOR PROFILES

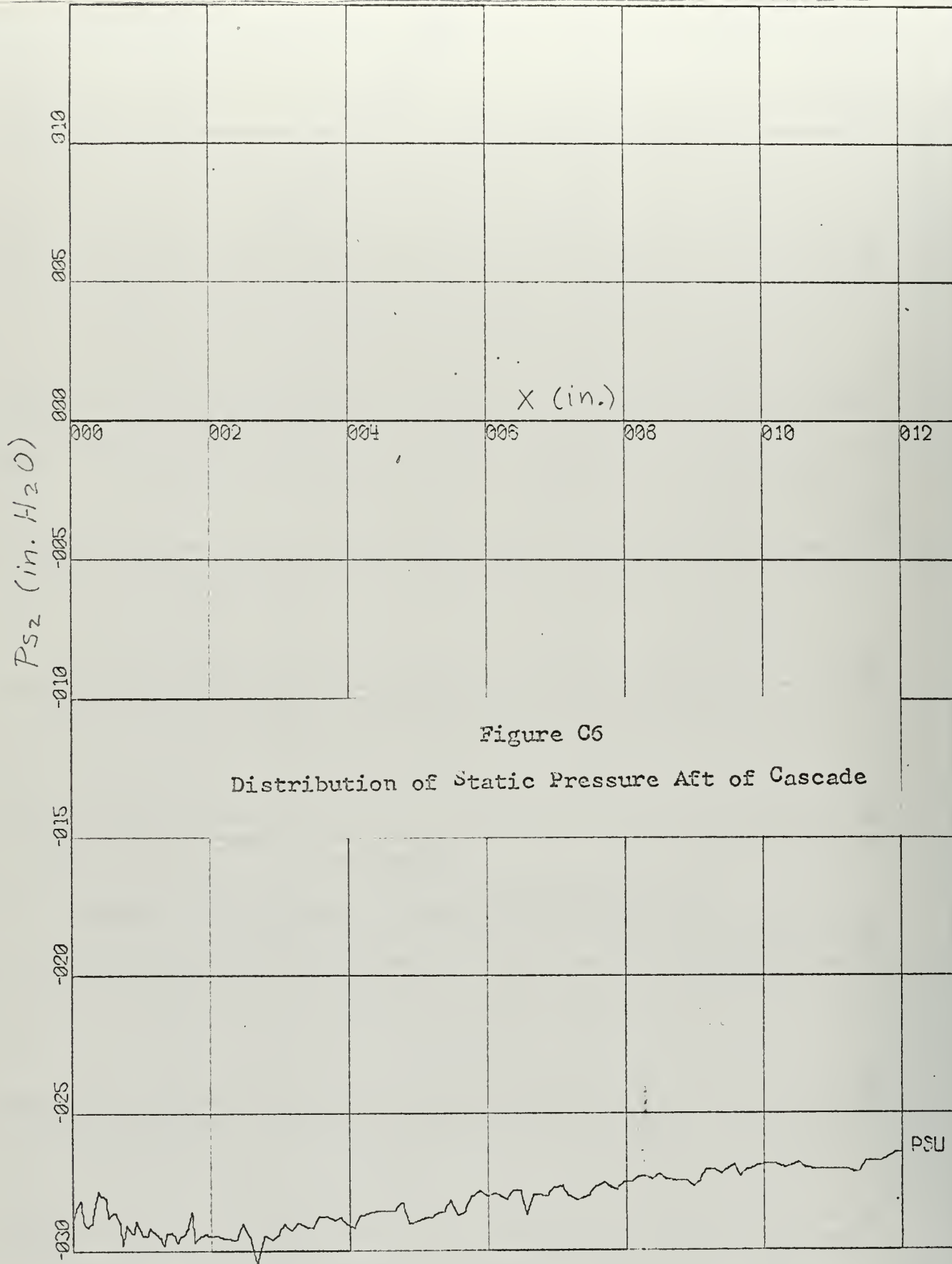


Figure C6

Distribution of Static Pressure Aft of Cascade

X-SCALE - 2.00E+00 UNITS/INCH.

Y-SCALE - 5.00E-01 UNITS/INCH.

RUN 300

STATOR PROFILES

Table C2
 PROPULSION LABORATORY
 U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 301

BAROMETRIC PRESS. = 30.13 IN. HG.

PLENUM TEMP. = 60.1 DEG. F.

STAGGER ANGLE = 48.00DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)				FAR AFT (STATION 3)			
V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
53.312	.00	2190.0	2186.5	229.918	78.67	2186.6	2122.5

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)		UPPER TRAVERSE (STATION 2)	
P11 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2190.0	2186.5	2186.6	2122.5

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAG
22.02	-8.14	23.44	1.36

TOTAL TURNING ANGLE OF THE FLOW (DEG) = -78.67

RUN NO. = 301 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .05088

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V0 AND V3

CL	CD
2.3024	.1332

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0	CD0
12.1233	.7012

CONSTRICION FACTOR = 1.2054

DELTA X LOWER = 12.00

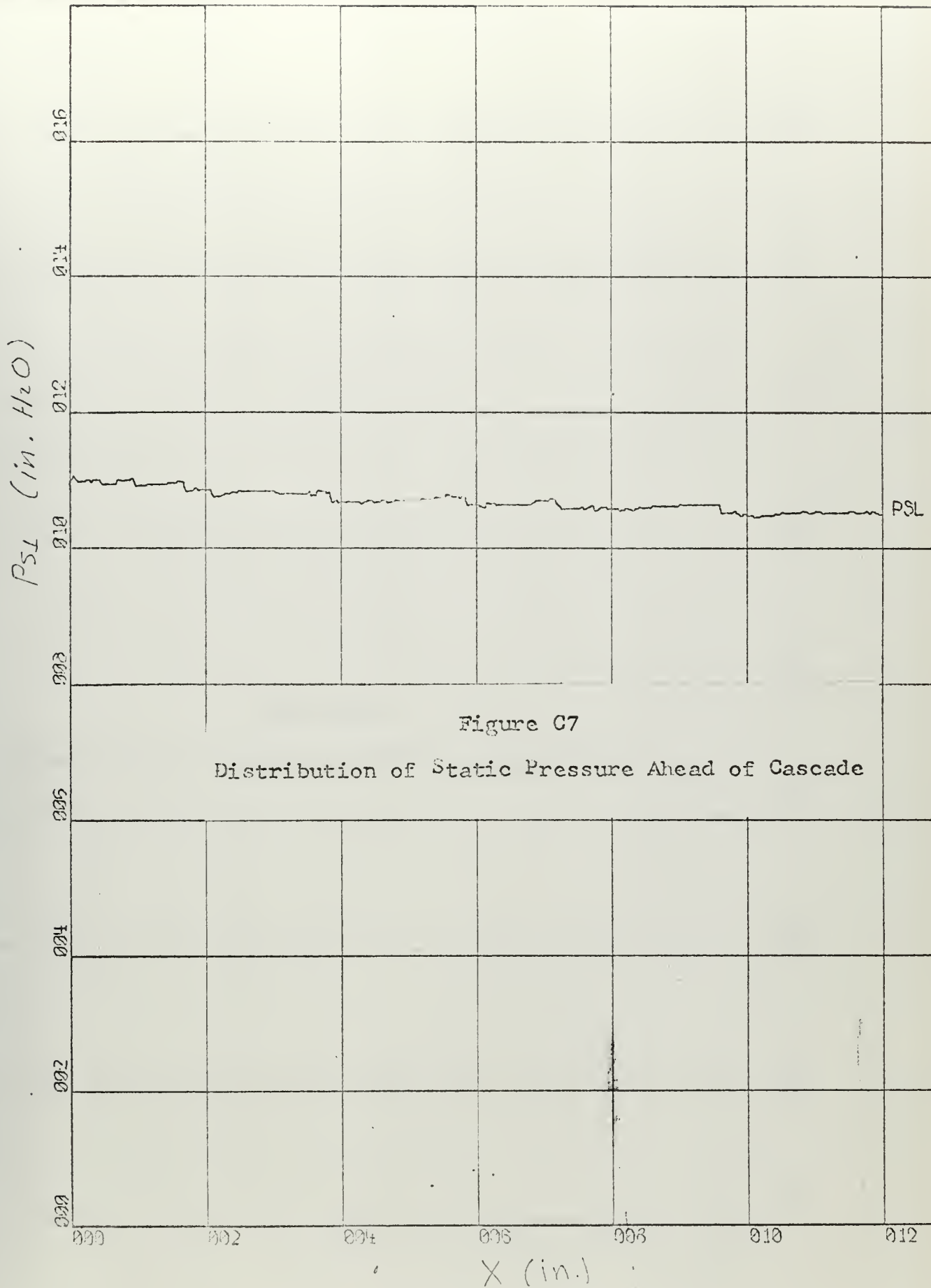
DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00245173

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00239820

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

806858.	.2057
TIME, 4 MINUTES AND 43 SECONDS	



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 301

113 STATOR PROFILES

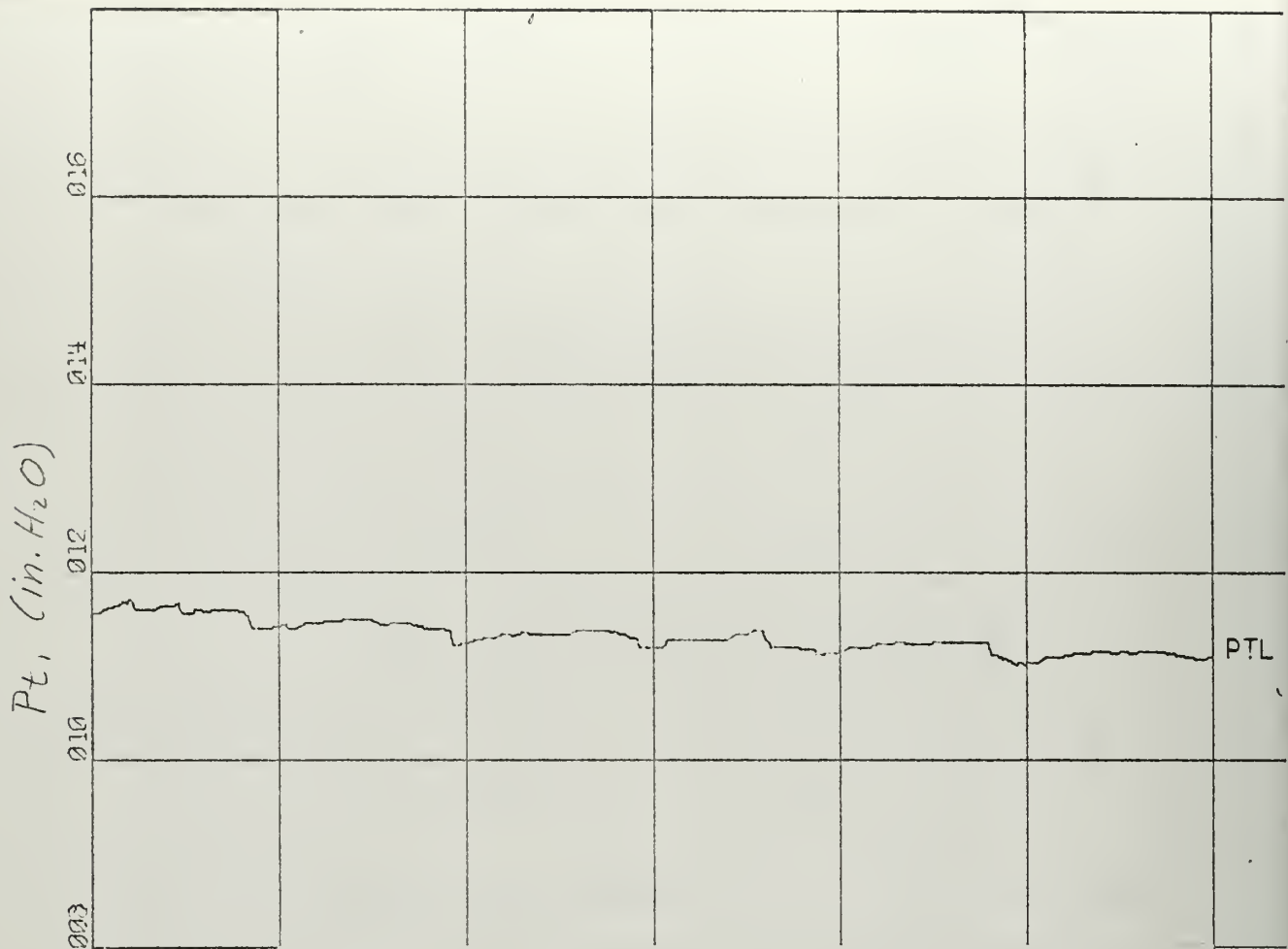
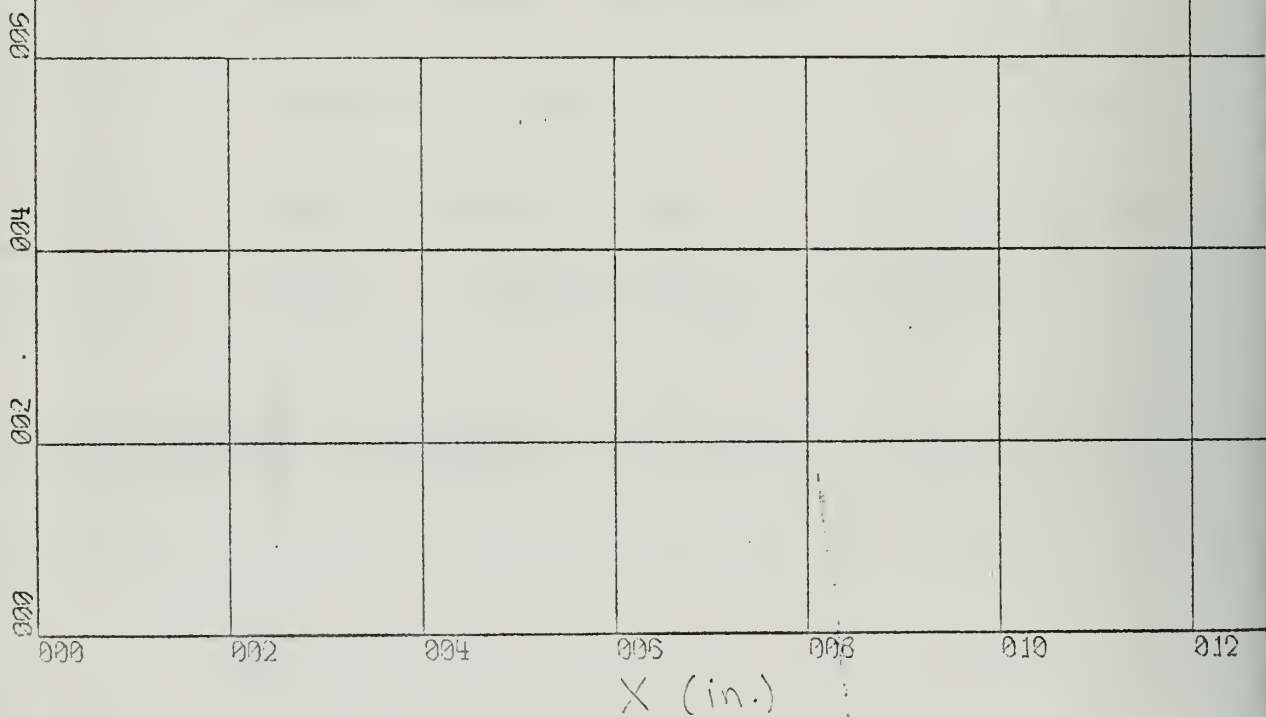


Figure C8

Distribution of Total Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 301

STATOR PROFILES

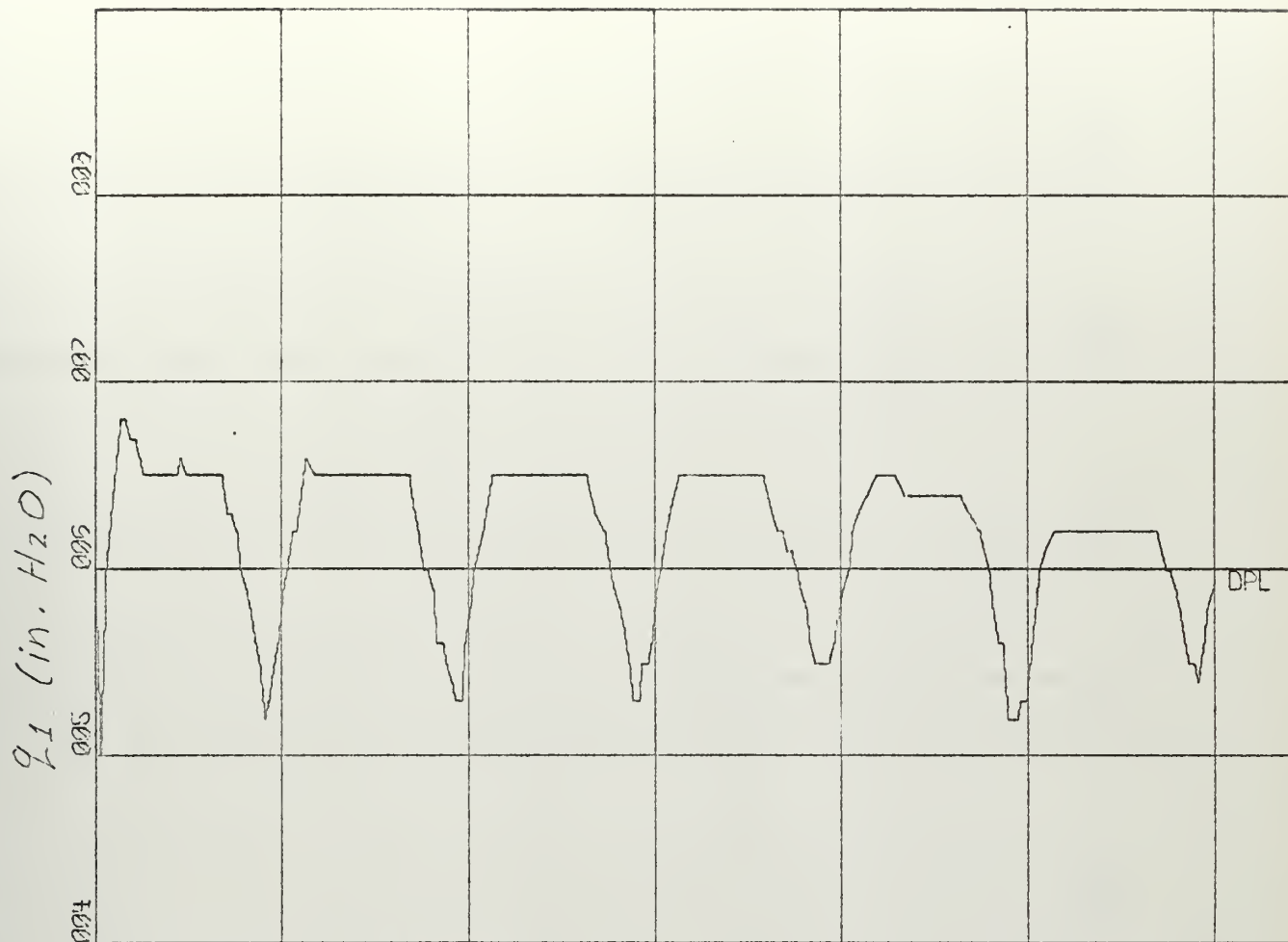
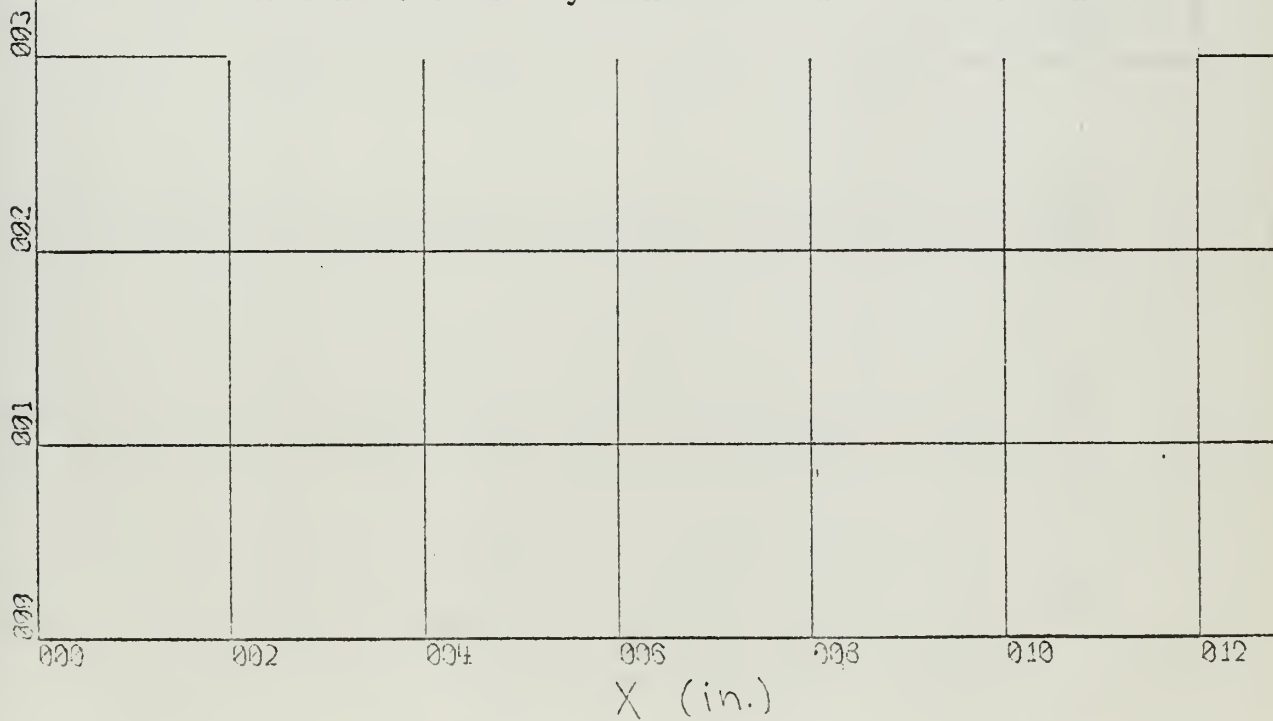


Figure C9

Distribution of Dynamic Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 1.00E-01 UNITS/INCH.

RUN 301

115 STATOR PROFILES

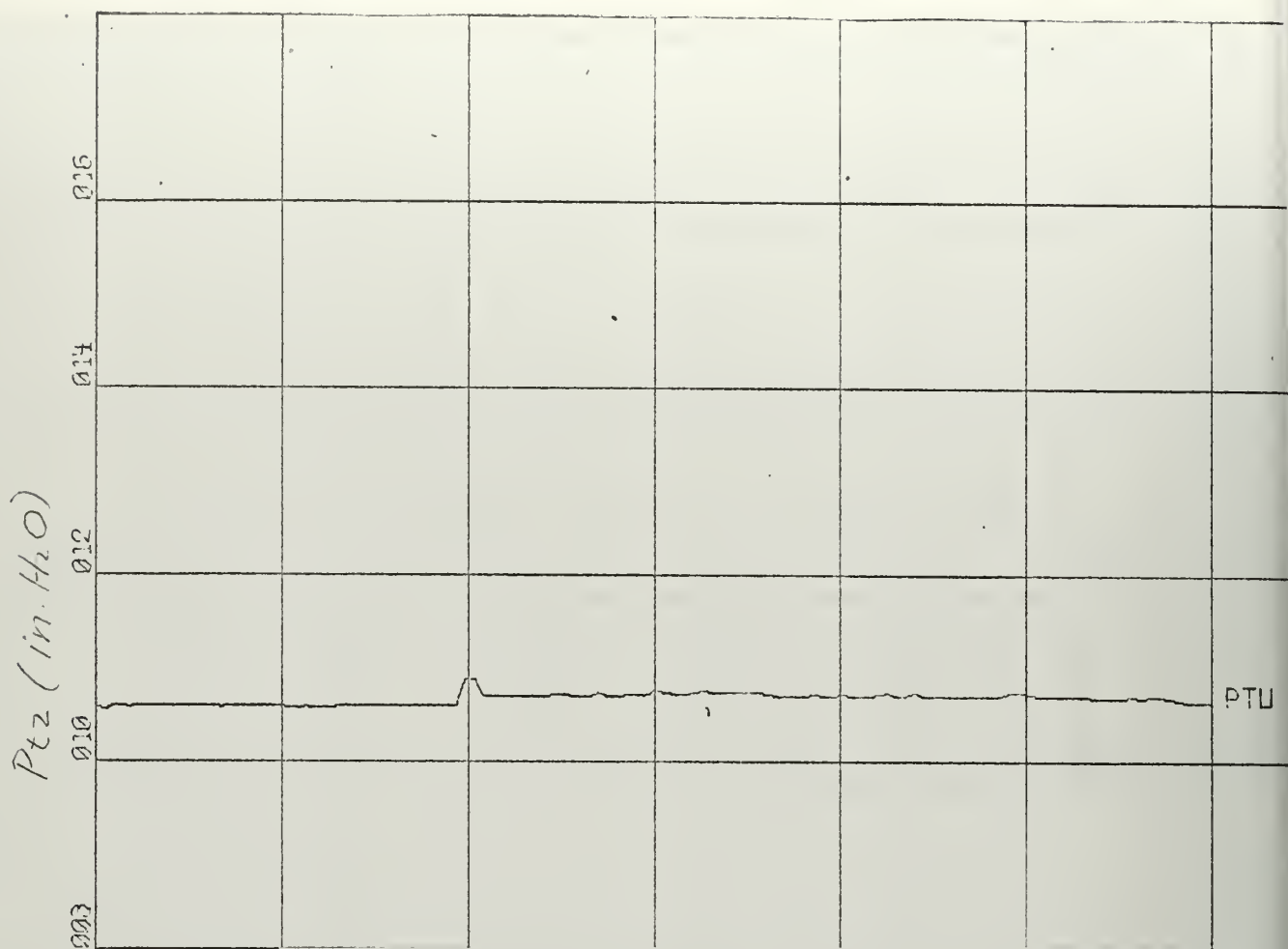
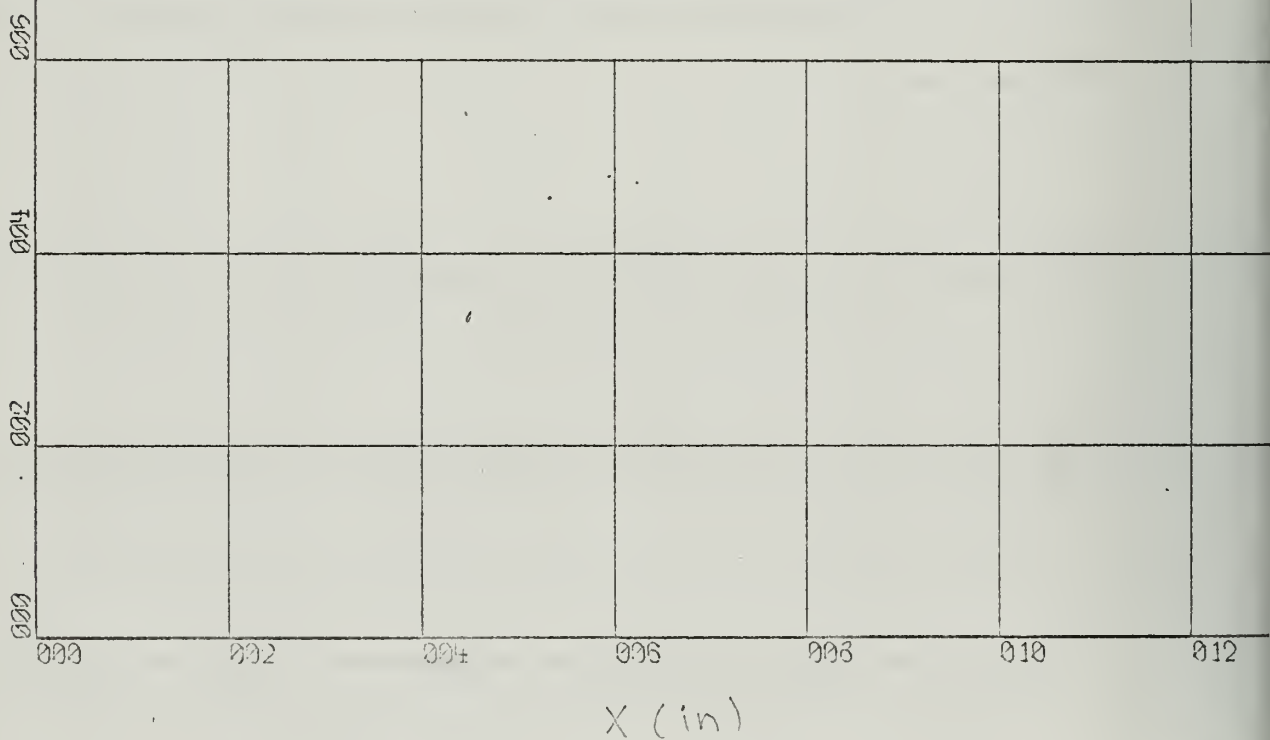


Figure C10

Distribution of Total Pressure Aft of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 301

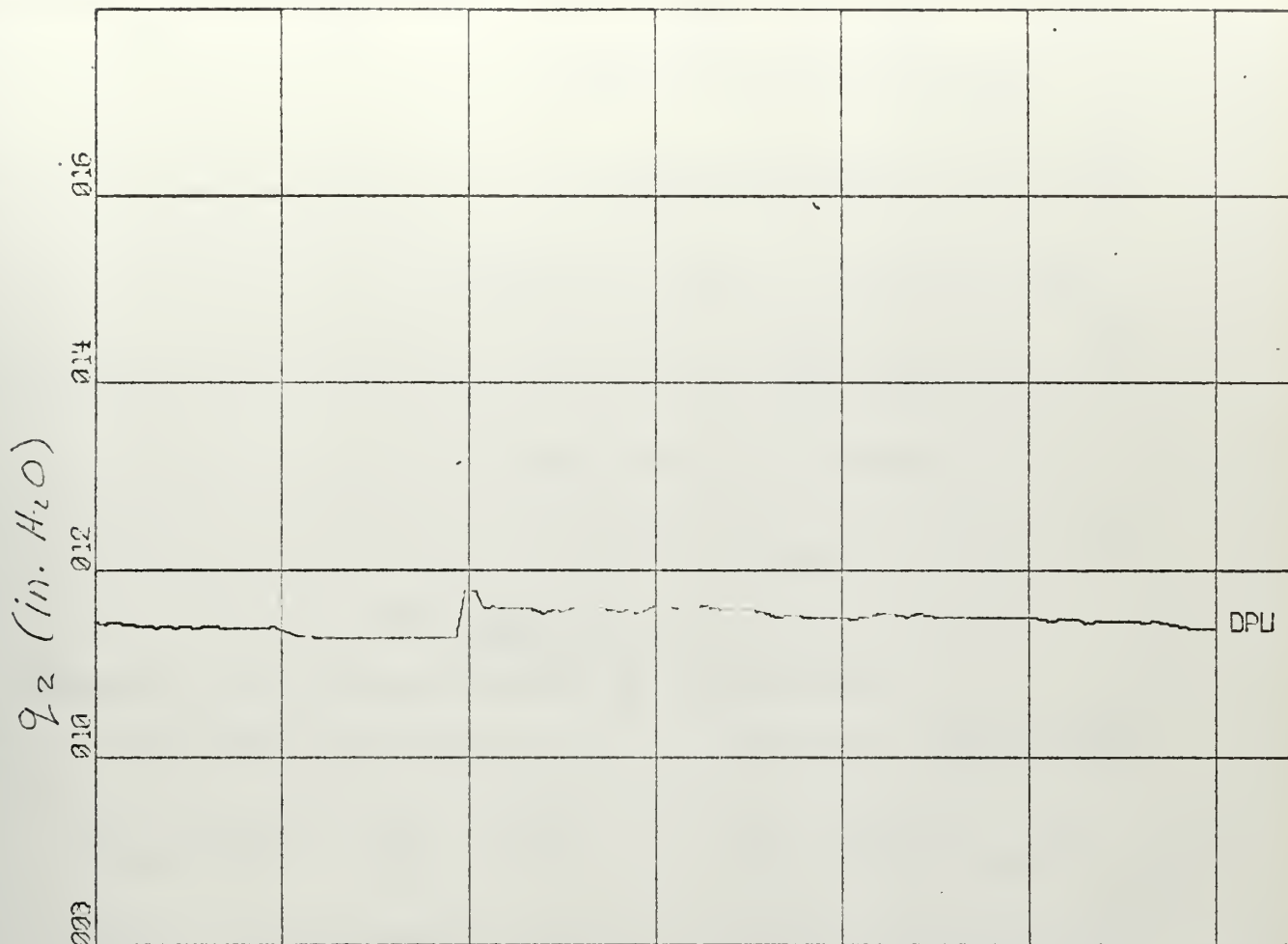
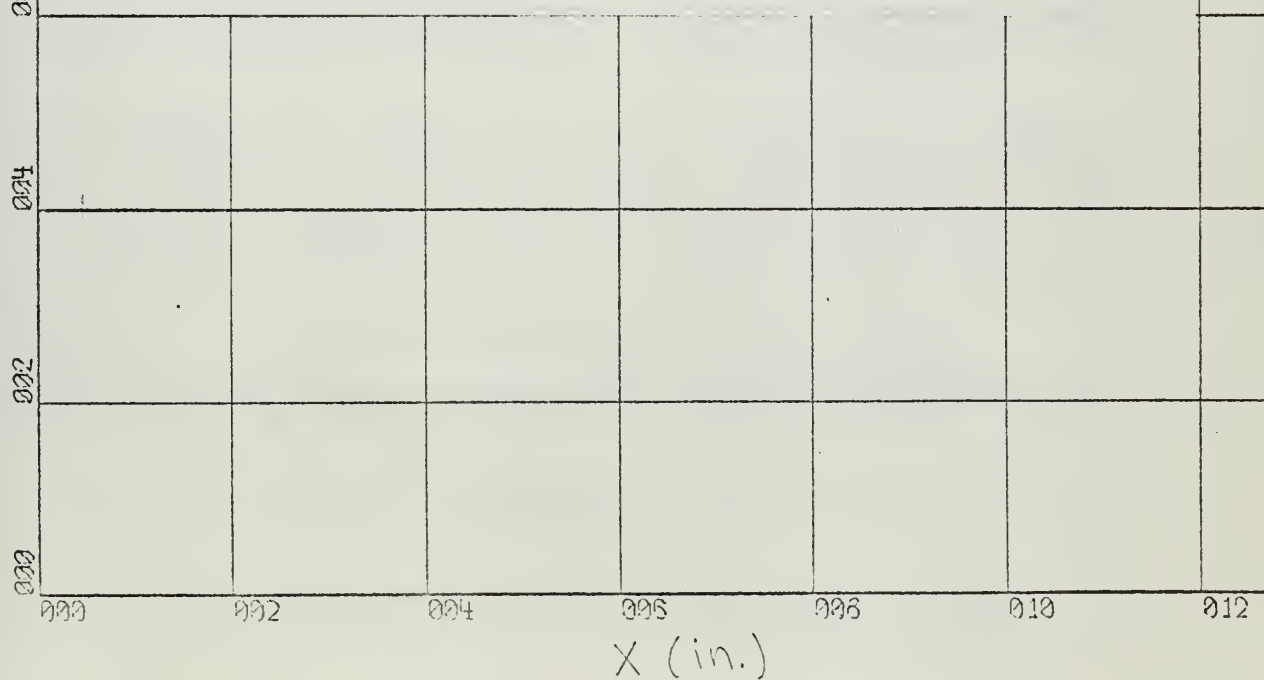


Figure C11

Distribution of Dynamic Pressure Aft of Cascade

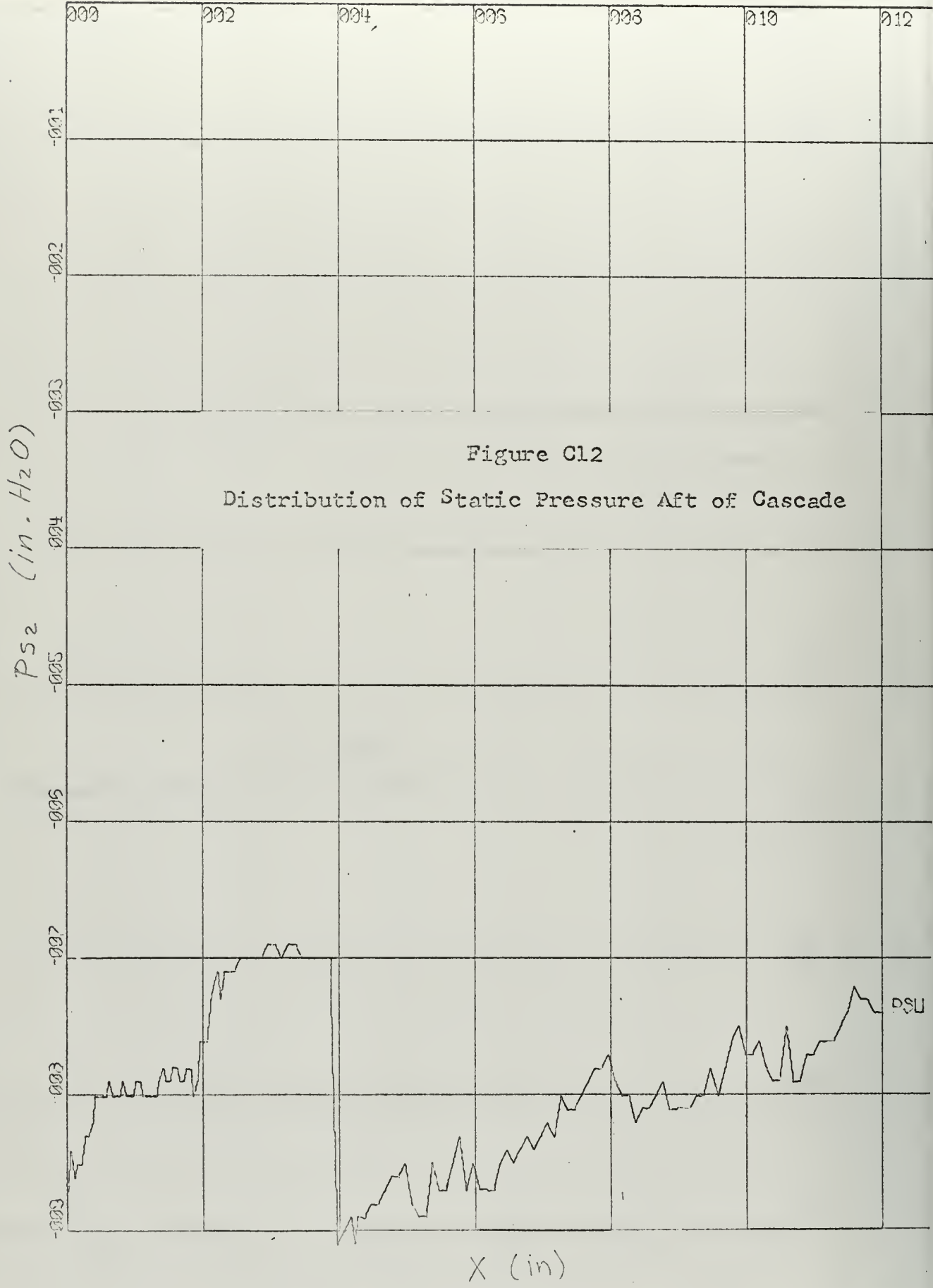


X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 301

STATOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 1.00E-01 UNITS/INCH.

RUN 301

118 STATOR PROFILES

Table C3

PROPULSION LABORATORY
U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 302

BAROMETRIC PRESS. = 30.05 IN. HG.

PLENUM TEMP. = 66.7 DEG. F.

STAGGER ANGLE = -4.50 DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)

FAR AFT (STATION 3)

V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
213.083	62.44	2256.3	2200.1	337.273	-71.88	2246.7	2108.5

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)

UPPER TRAVERSE (STATION 2)

PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2256.3	2200.1	2246.9	2108.5

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAW
29.78	41.85	51.32	2.27

TOTAL TURNING ANGLE OF THE FLOW (DEG) = 134.33

RUN NO. = 302 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .06316

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V0 AND V3

CL

CD

5.2188

.2313

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0

CD0

1.6614

.0736

CONSTRICITION FACTOR = .9701

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00245261

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00237540

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

1160648.

.1895

TIME, 5 MINUTES AND 18 SECONDS.

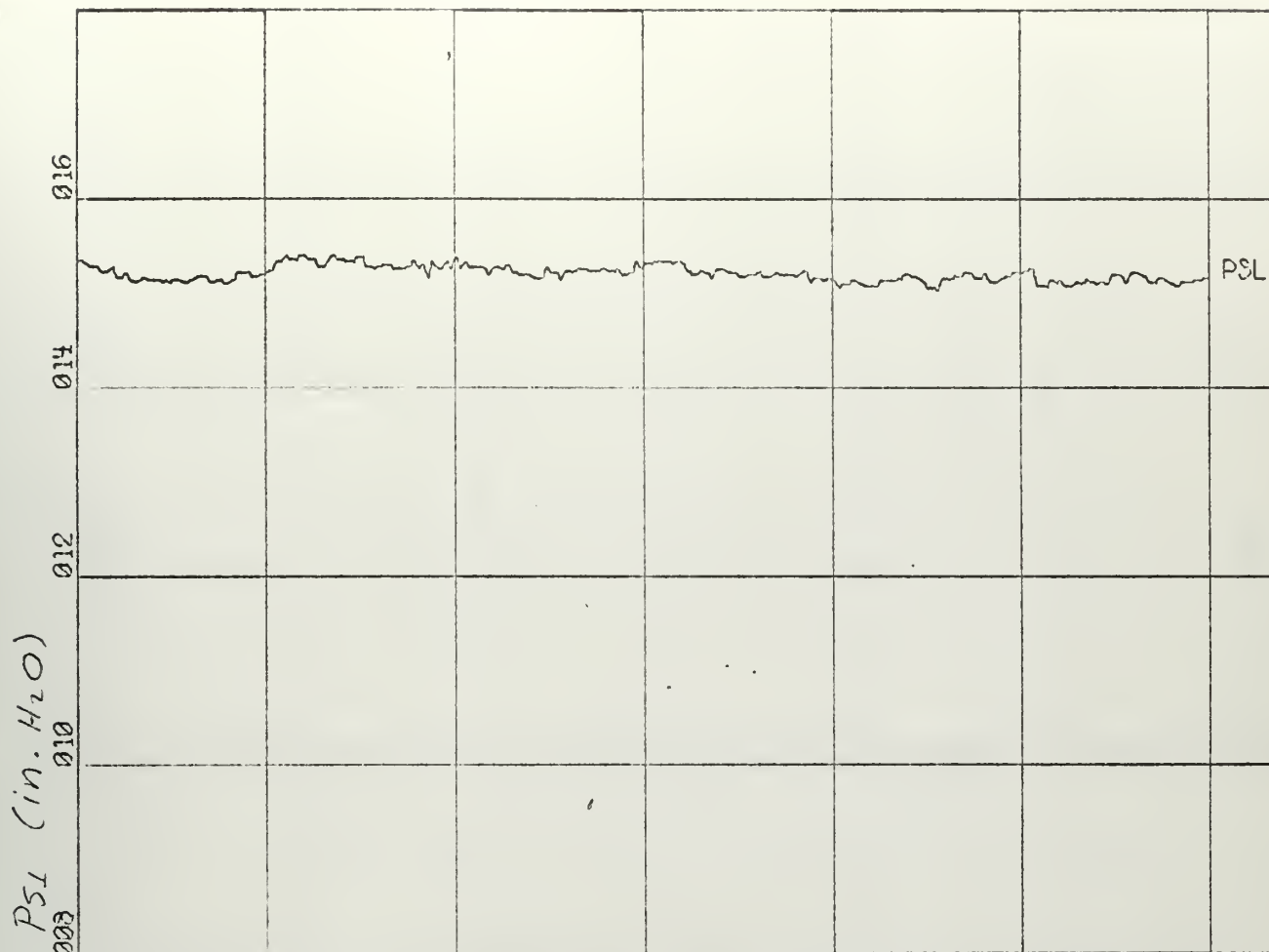
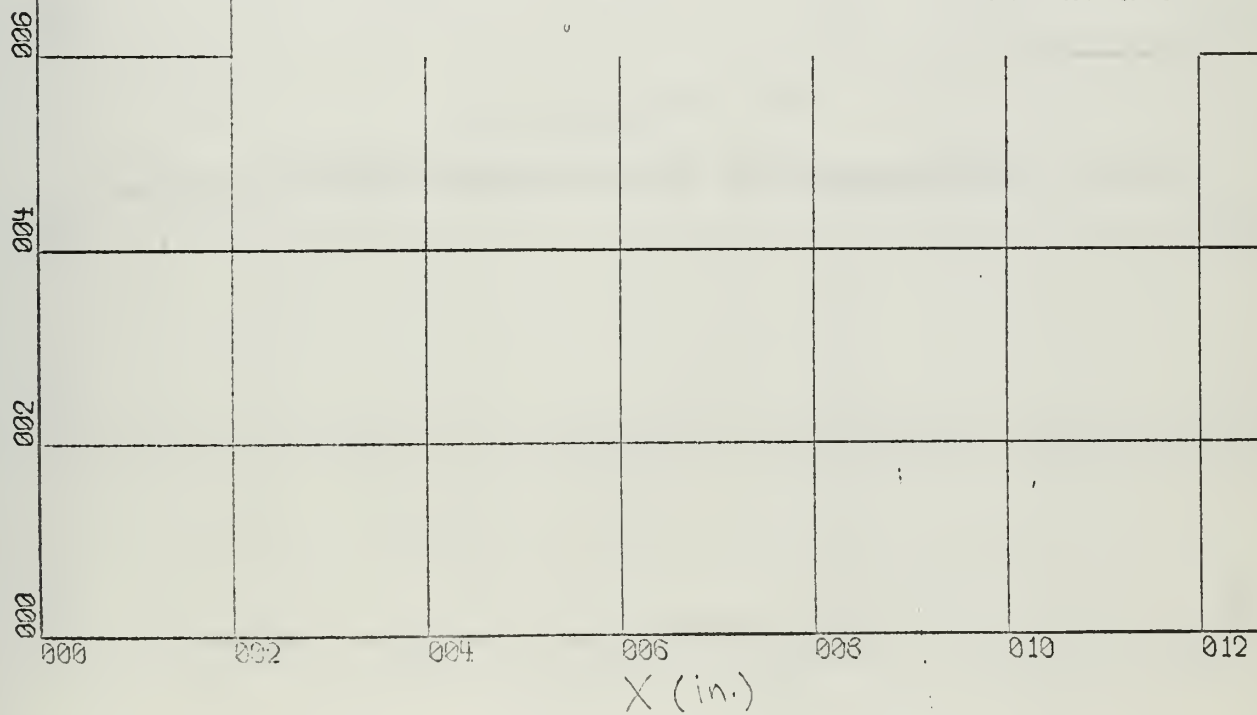


Figure C13

Distribution of Static Pressure Ahead of Cascade



X-SCALE - 2.00E+00 UNITS/INCH.

Y-SCALE - 2.00E+00 UNITS/INCH.

RUN 302

ROTOR PROFILES

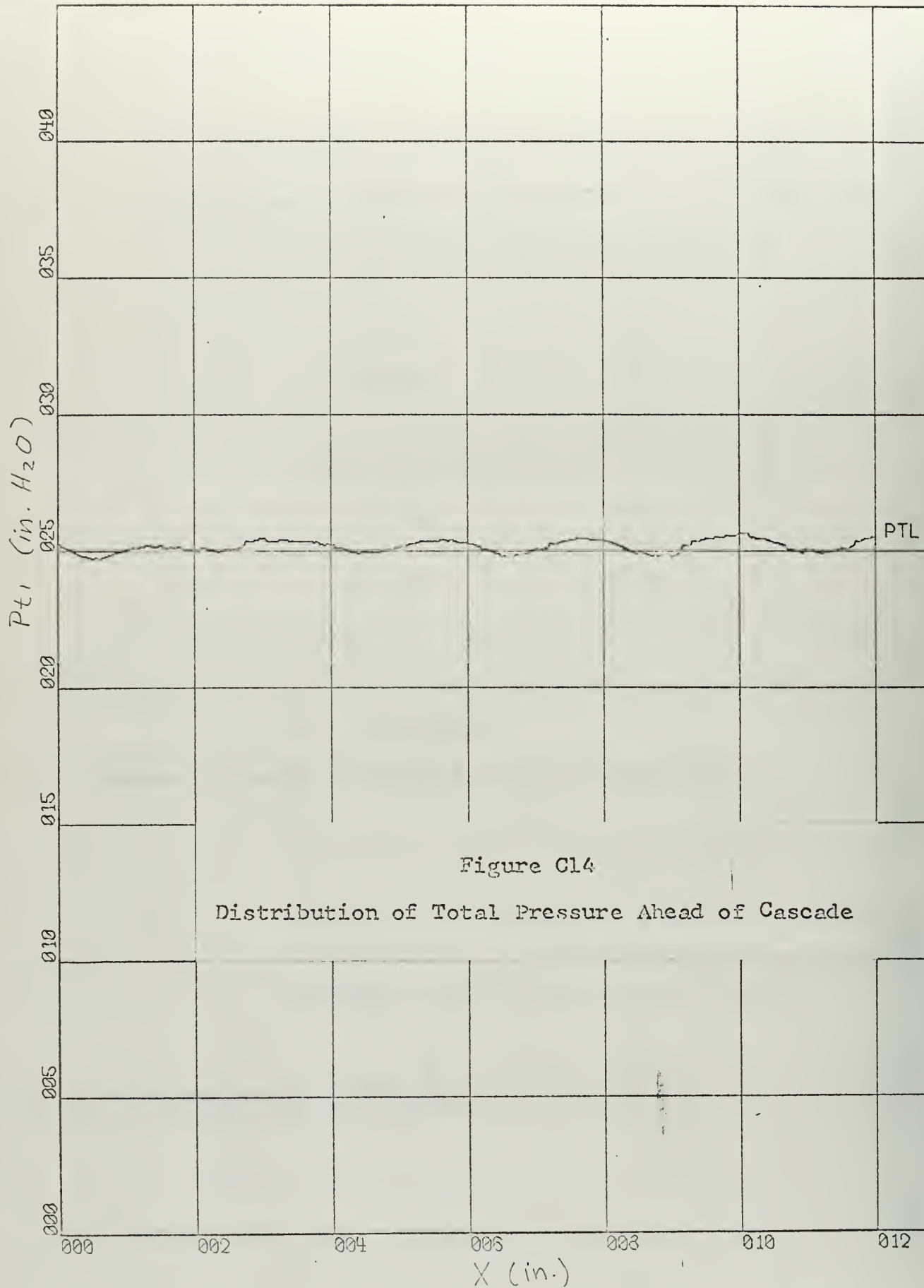
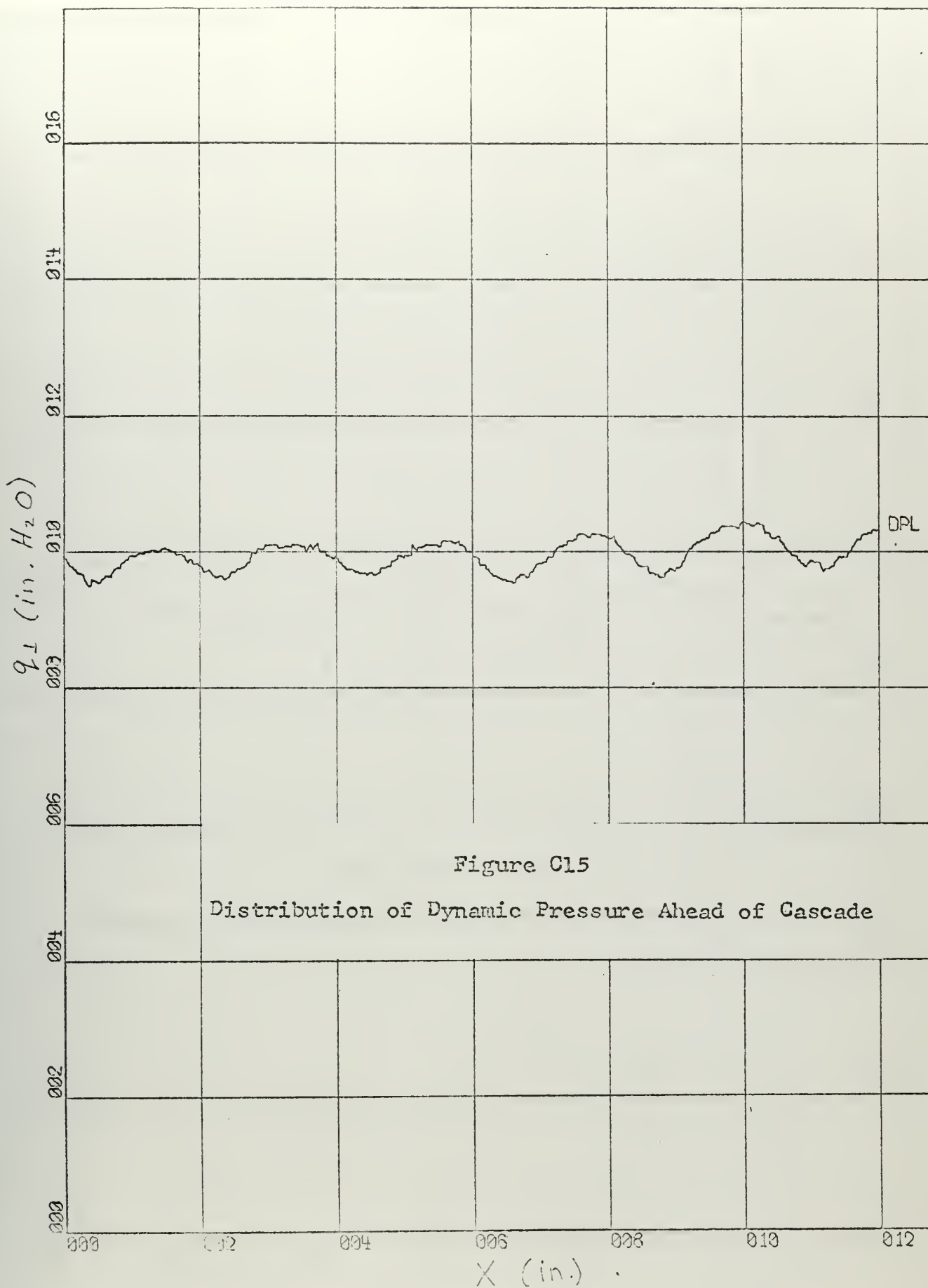


Figure C14
Distribution of Total Pressure Ahead of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 302

129 ROTOR PROFILES

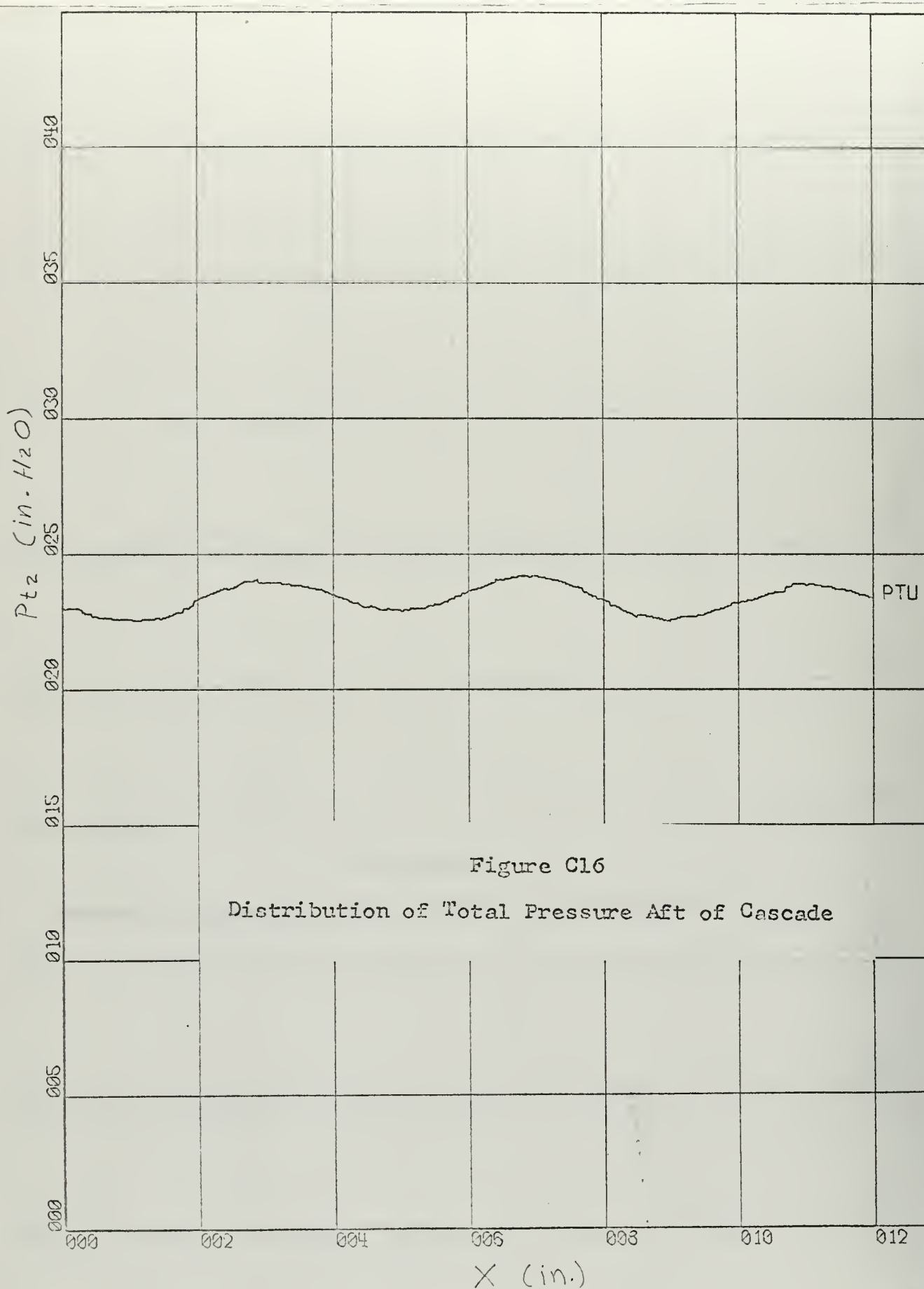


X-SCALE - 2.00E+00 UNITS/INCH.

Y-SCALE - 2.00E+00 UNITS/INCH.

RUN 302

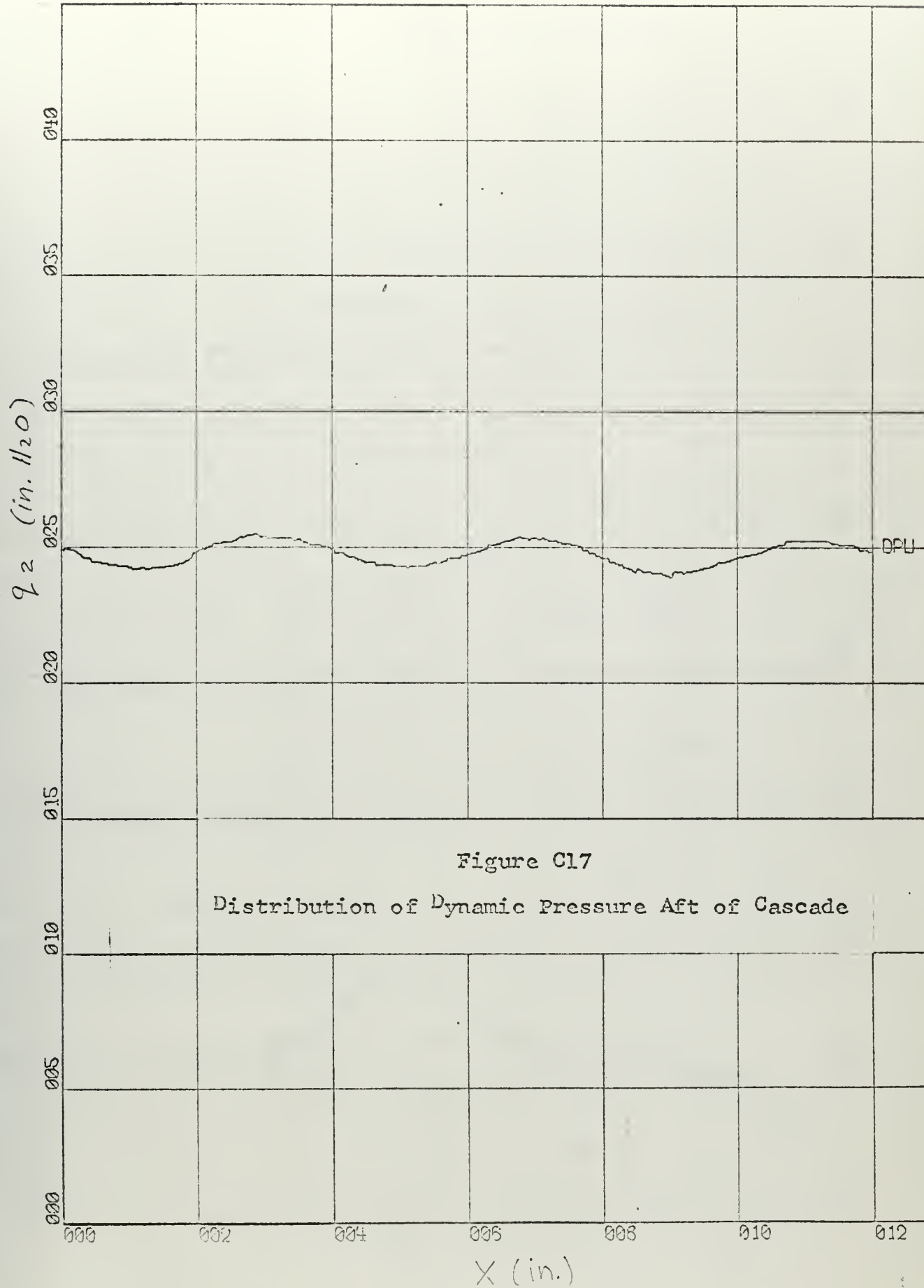
ROTOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 302

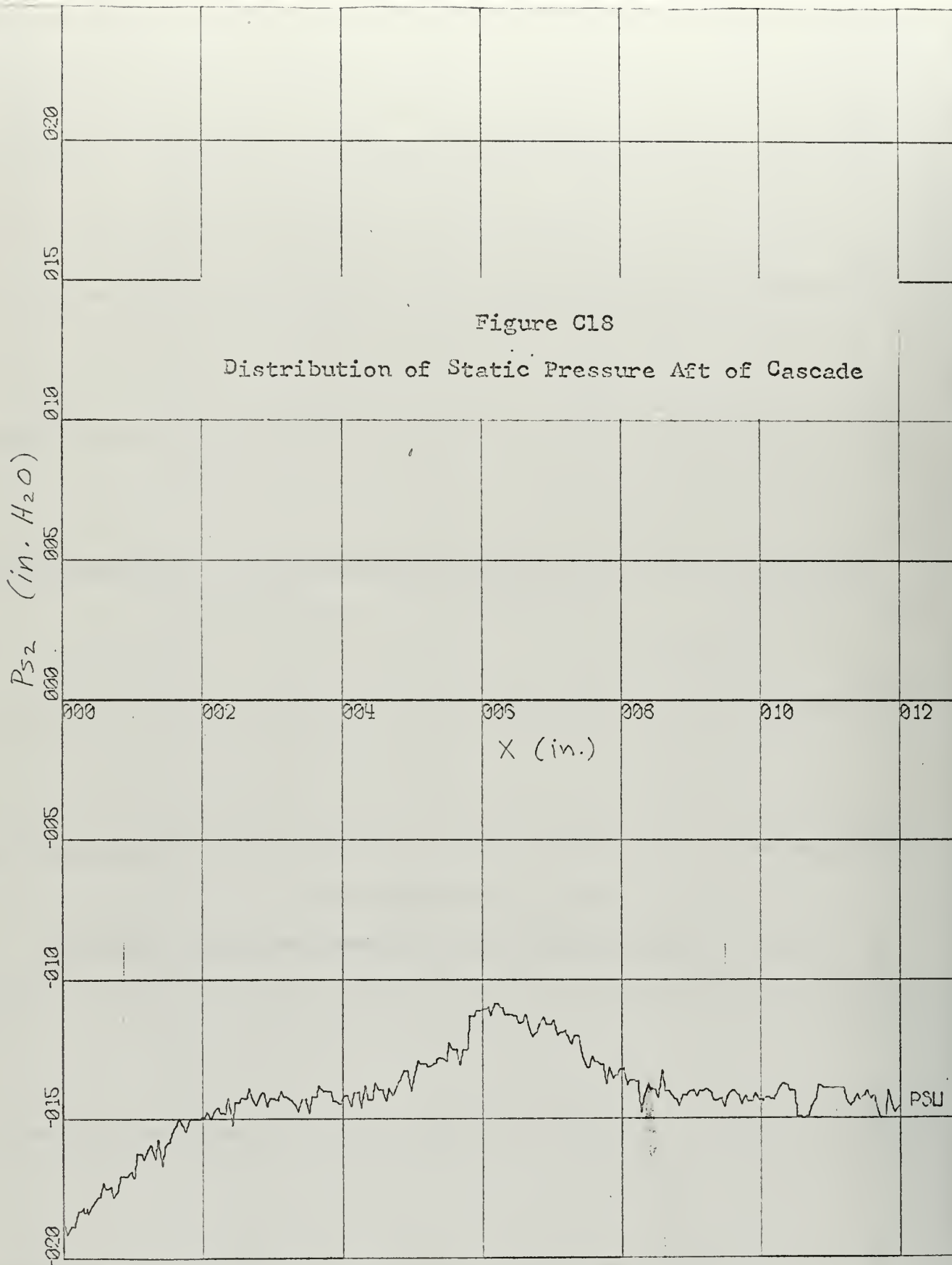


X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 302

125 ROTOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E-01 UNITS/INCH.

RUN 302

ROTOR PROFILES

TABLE 1
 PROPULSION LABORATORY
 U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 303

BAROMETRIC PRESS. = 30.05 IN. HG.

PLENUM TEMP. = 68.0 DEG. F.

STAGGER ANGLE = -4.50DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)				FAR AFT (STATION 3)			
V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
238.464	66.23	2256.5	2186.5	336.382	-71.59	2247.2	2109.9

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)		UPPER TRAVERSE (STATION 2)	
PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2256.5	2186.5	2247.3	2109.9

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAG
24.08	43.83	49.97	1.99

TOTAL TURNING ANGLE OF THE FLOW (DEG) = 137.82

RUN NO. = 303 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .06190

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V_0 AND V_3

CL

CD

5.8628

.2333

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0

CD0

1.3007

.0518

CONSTRICION FACTOR = .9291

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00243577

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00237080

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

1153177.

.2118

TIME, 5 MINUTES AND 17 SECONDS

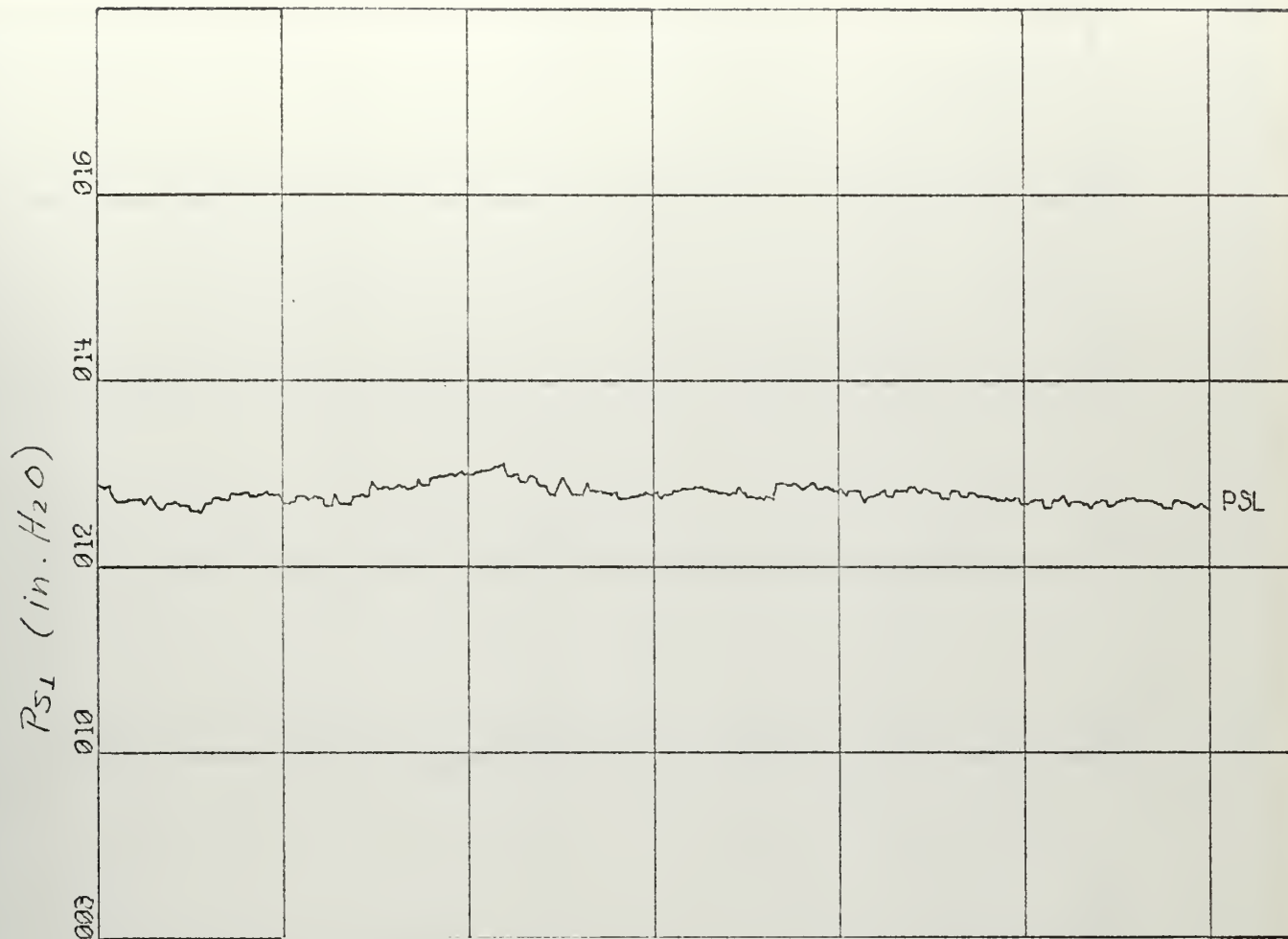
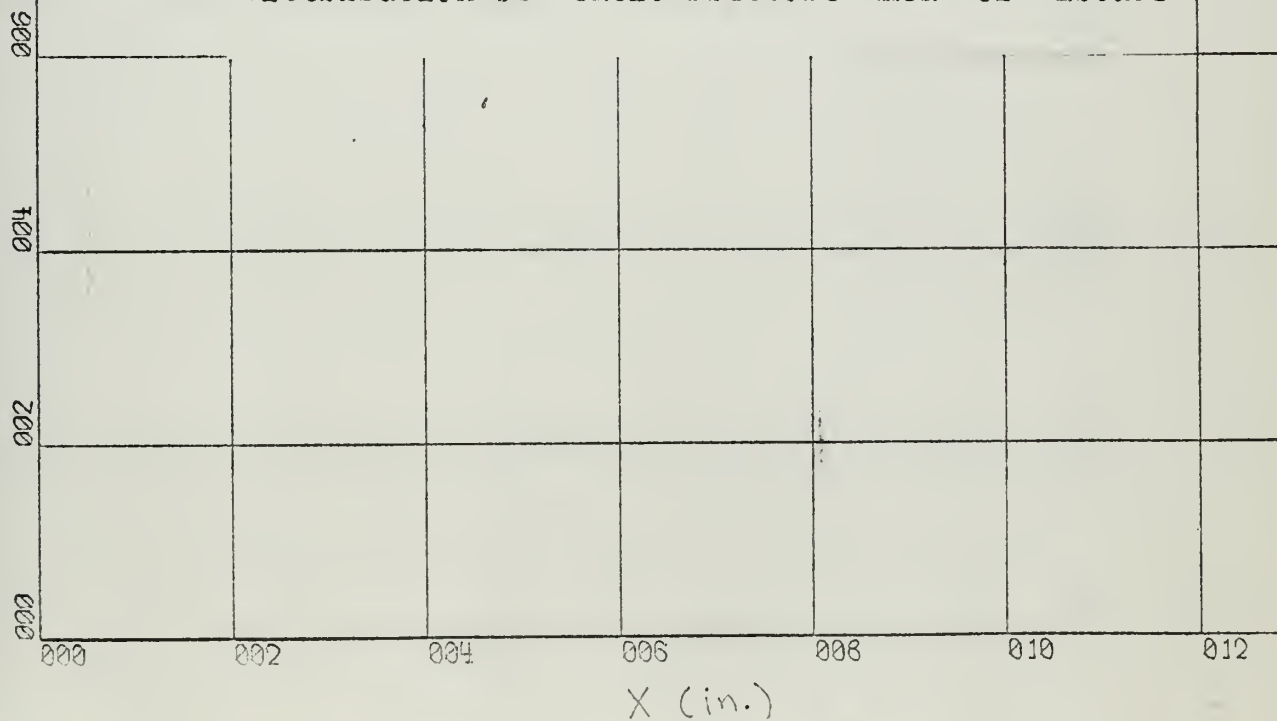


Figure C19

Distribution of Static Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 303

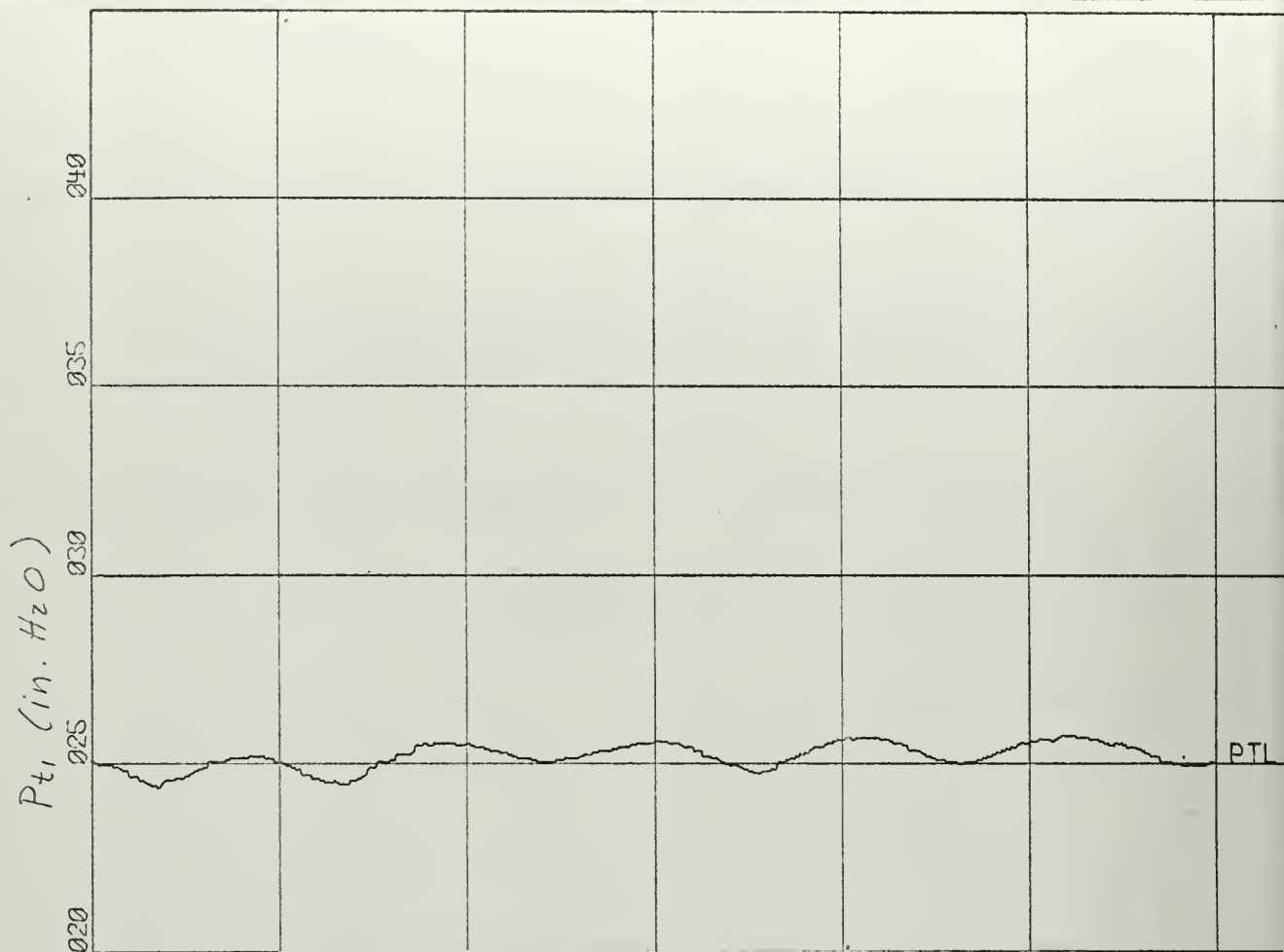
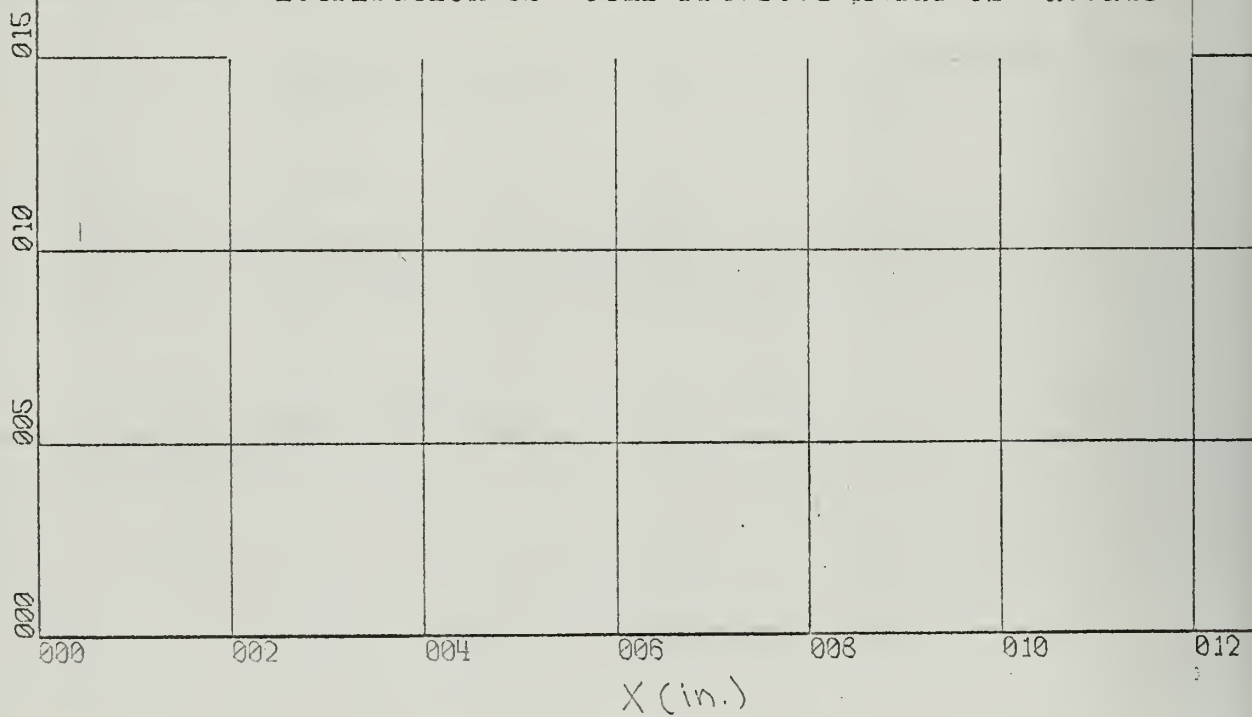


Figure C20

Distribution of Total Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 303

ROTOR PROFILES

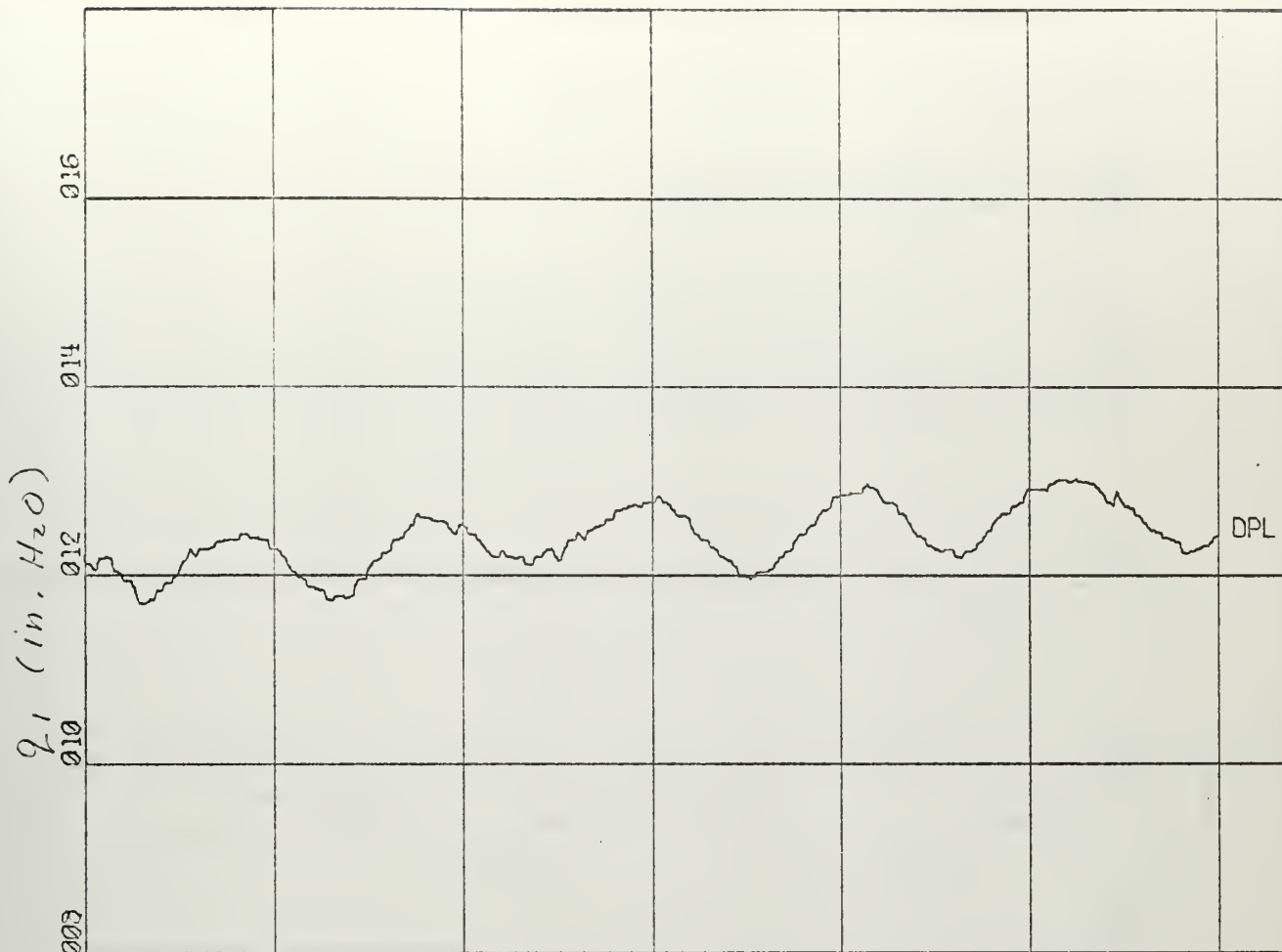
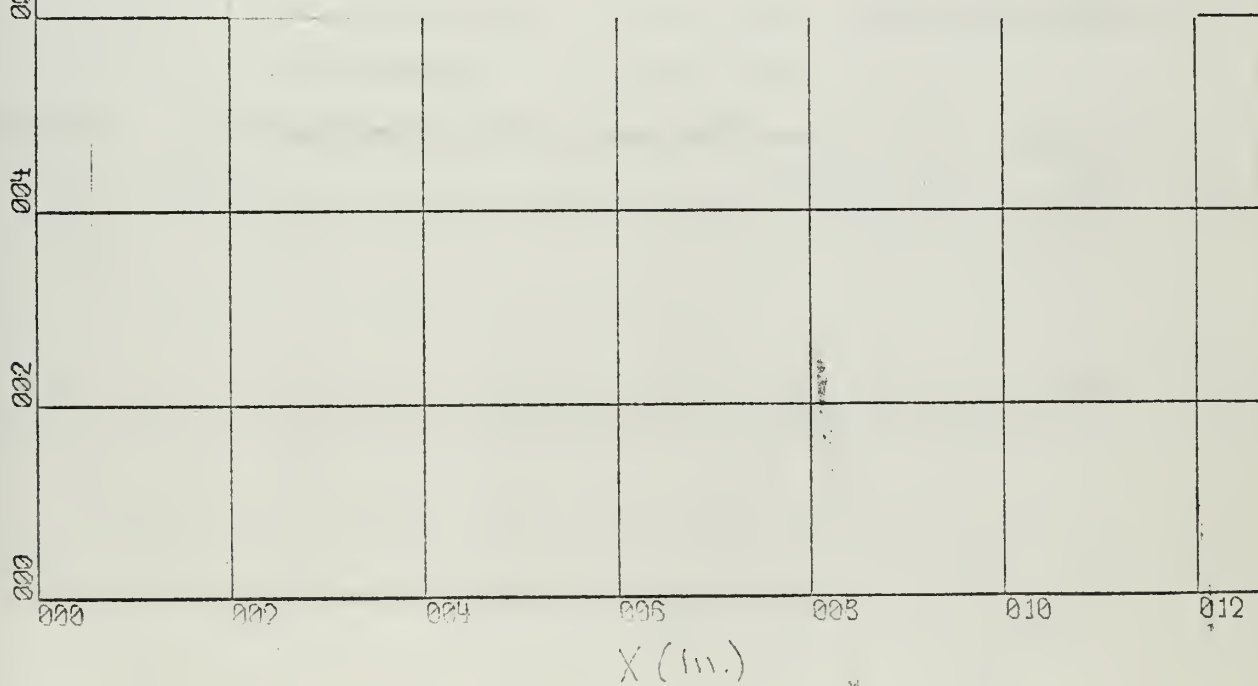


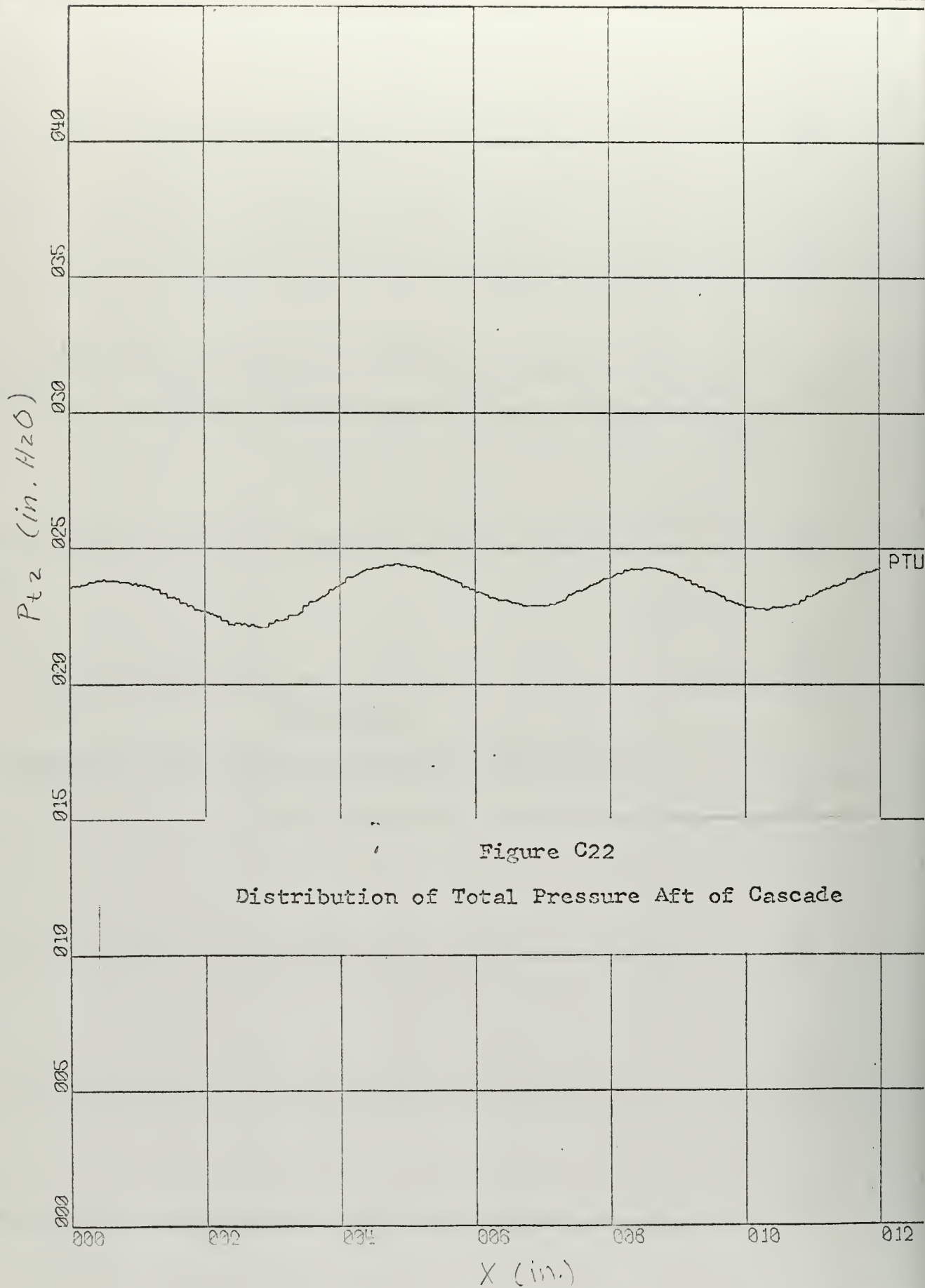
Figure C21
Distribution of Dynamic Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 303



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 303

132 ROTOR PROFILES

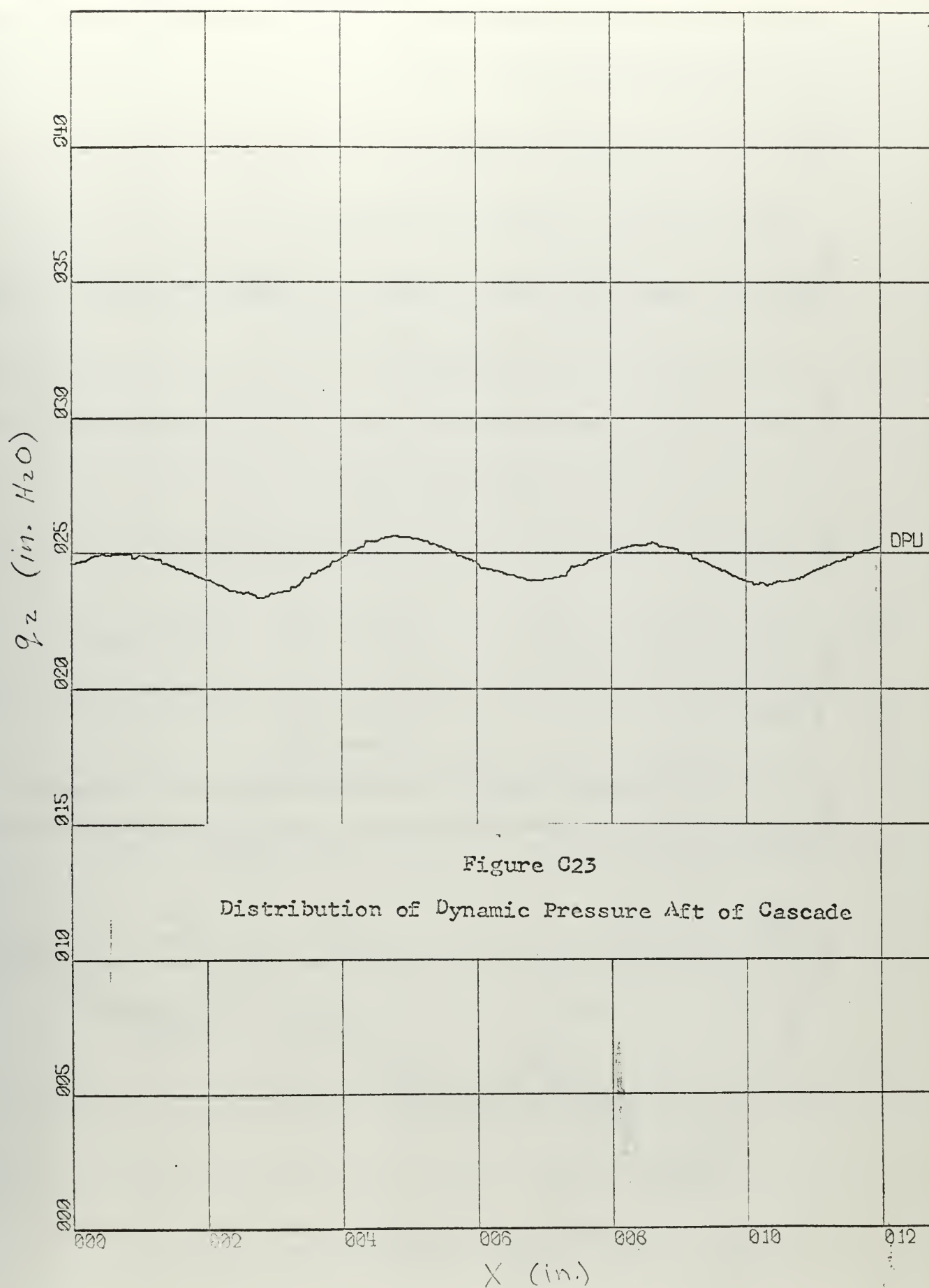


Figure C23

Distribution of Dynamic Pressure Aft of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 303

133

ROTOR PROFILES

P_{S2} (in. H_2O)

002

000

-002

-004

-006

-008

-010

-012

-014

000

002

004

006

008

010

012

X (in.)

Figure C24

Distribution of Static Pressure Aft of Cascade

PSU

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E-01 UNITS/INCH.

RUN 303

134 ROTOR PROFILES

Table C5

PROPULSION LABORATORY
U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 304

BAROMETRIC PRESS. = 30.10 IN. HG.

PLENUM TEMP. = 71.8 DEG. F.

STAGGER ANGLE = -4.50DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)				FAR AFT (STATION 3)			
V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
183.870	59.37	2258.4	2216.8	330.799	-72.41	2246.8	2114.9

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)		UPPER TRAVERSE (STATION 2)	
PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2258.4	2216.8	2246.9	2114.9

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAW
33.26	36.85	49.57	2.62

TOTAL TURNING ANGLE OF THE FLOW (DEG) = 131.78

RUN NO. = 304 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .08053

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V_0 AND V_3

CL	CD
4.7885	.2528

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0	CD0
2.1639	.1142

CONSTRICTION FACTOR = .9708

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00244289

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00235770

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

	1121636.	.1627
TIME, 4 MINUTES AND	0 SECONDS	

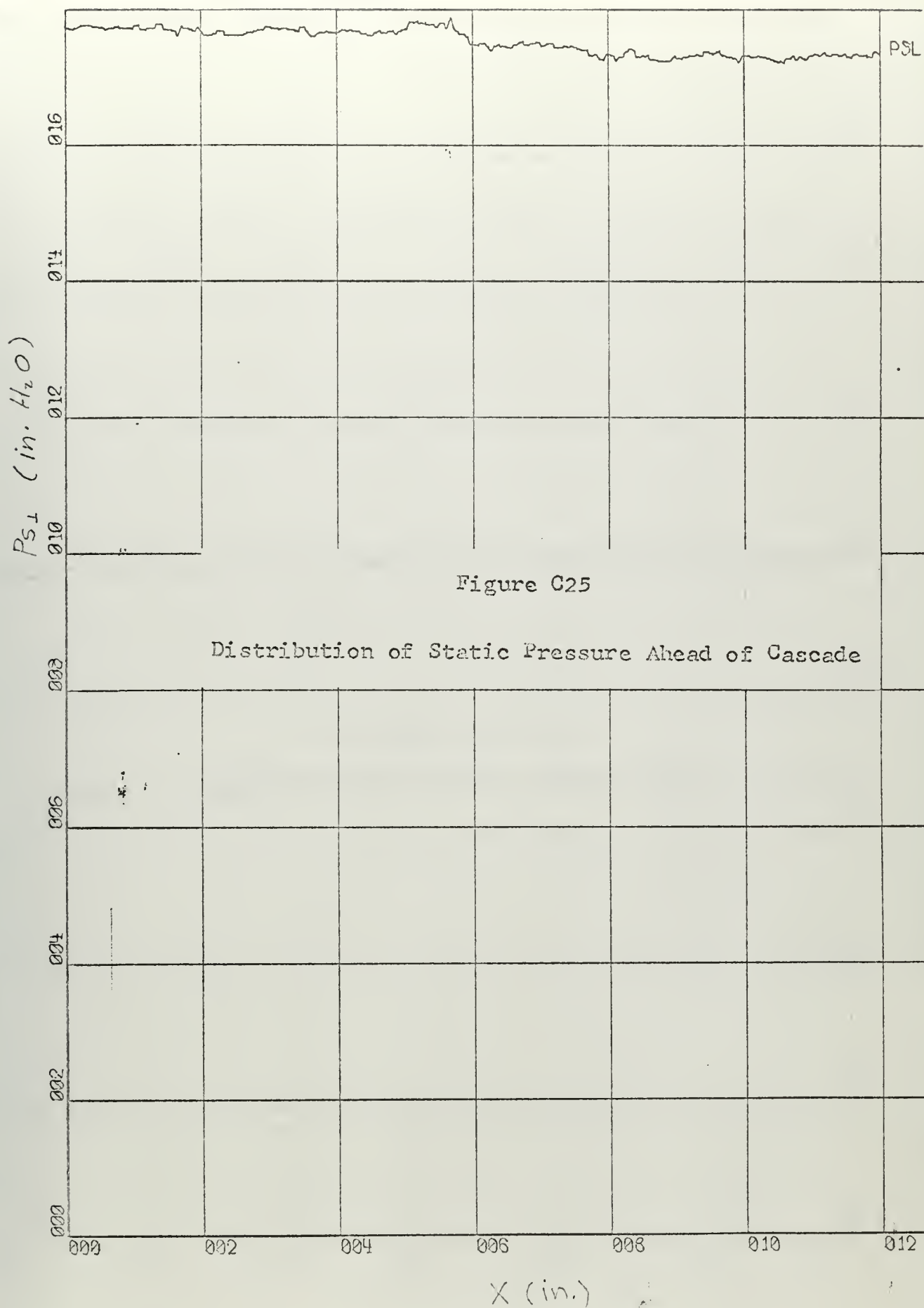


Figure C25

Distribution of Static Pressure Ahead of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 304

137 ROTOR PROFILES

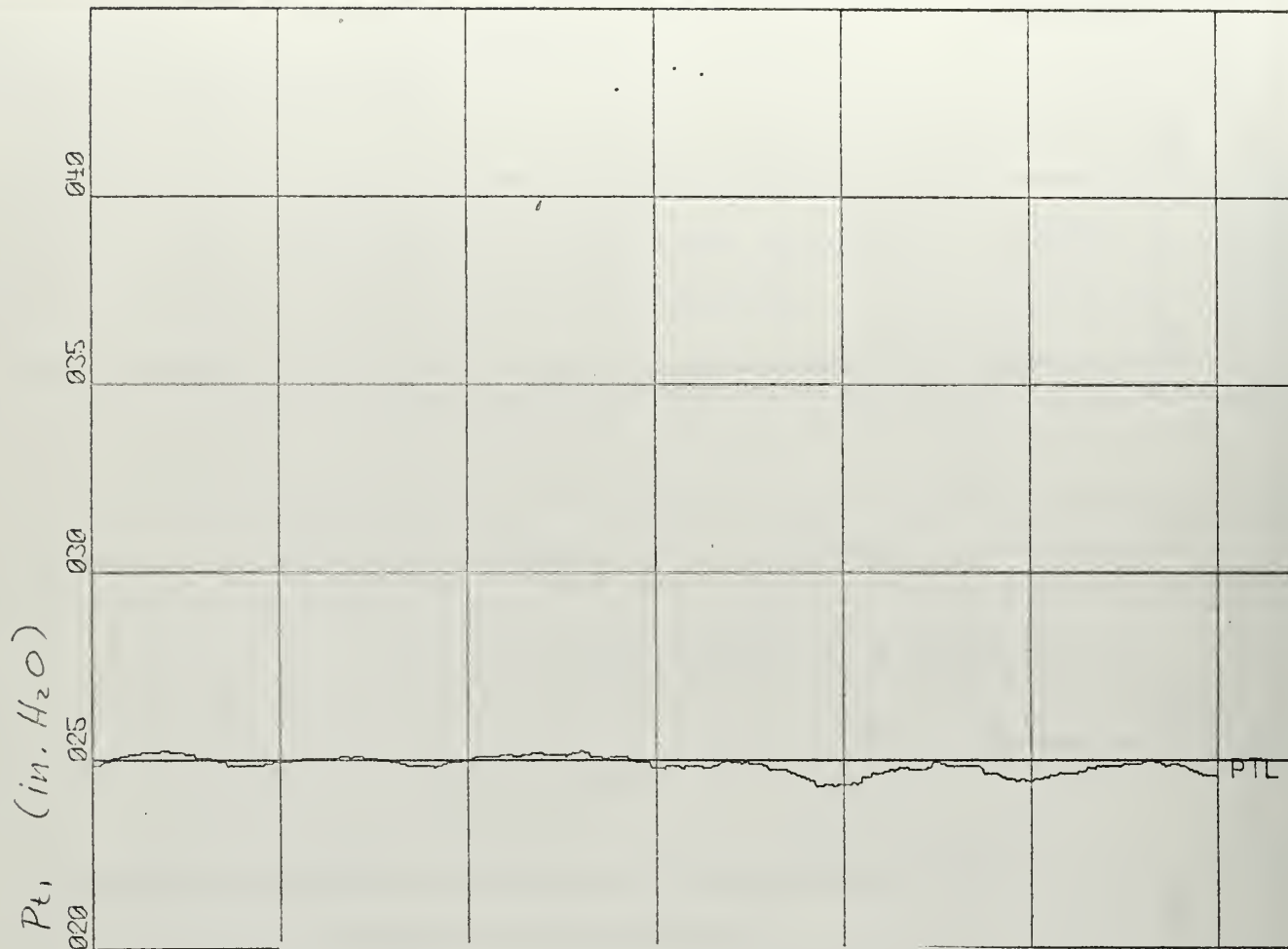
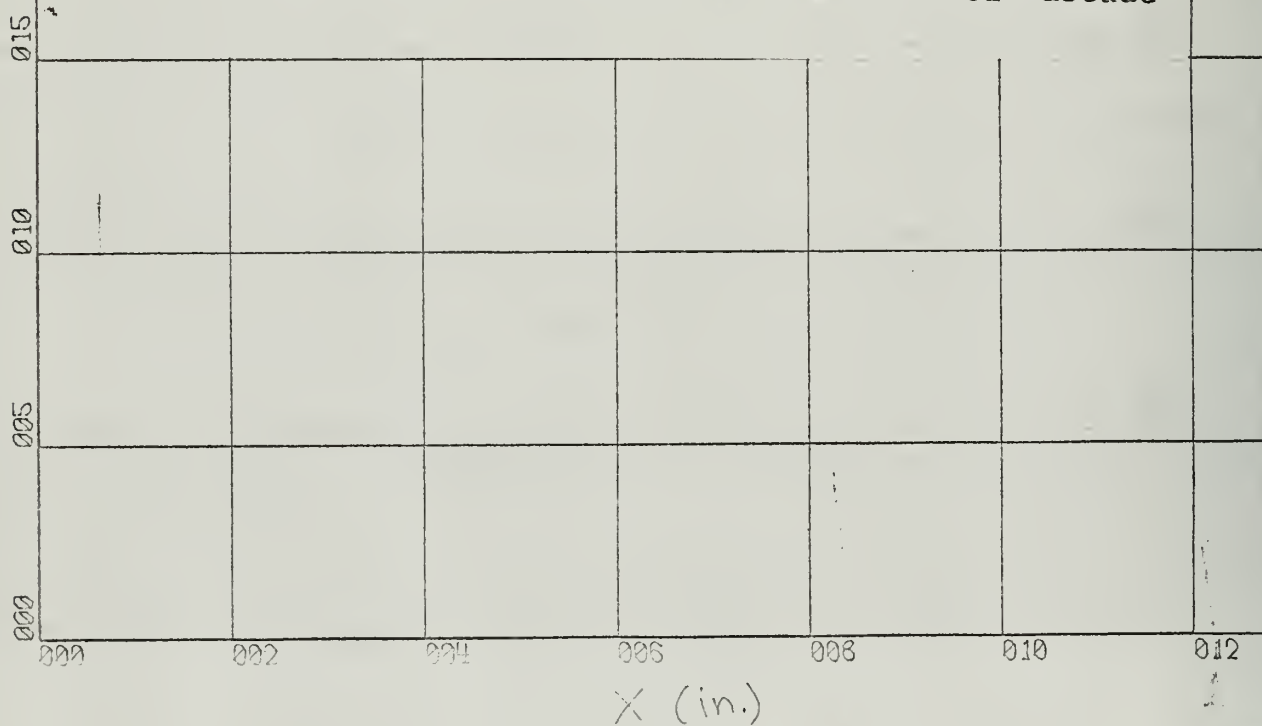


Figure C26

Distribution of Total Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 304

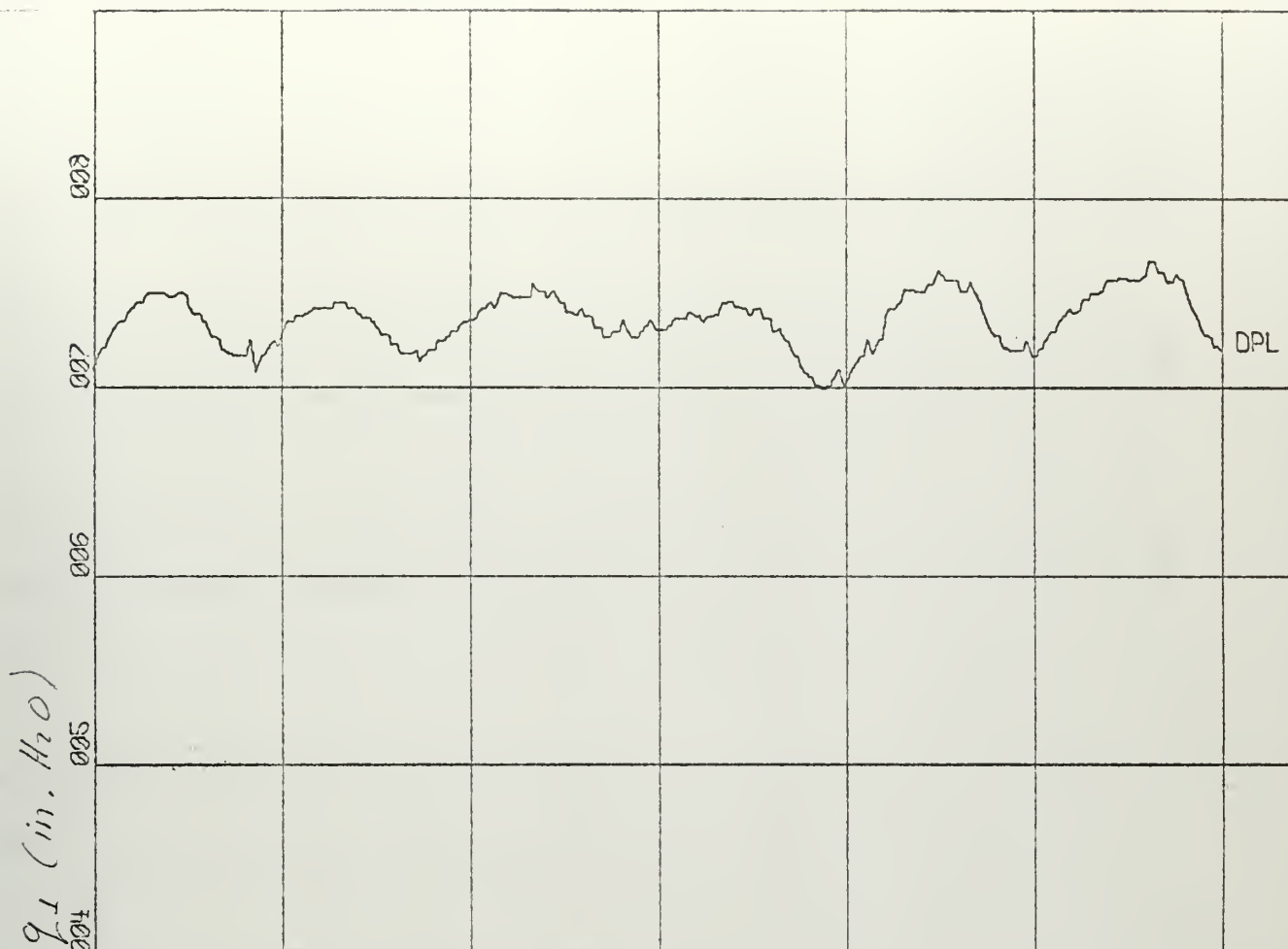
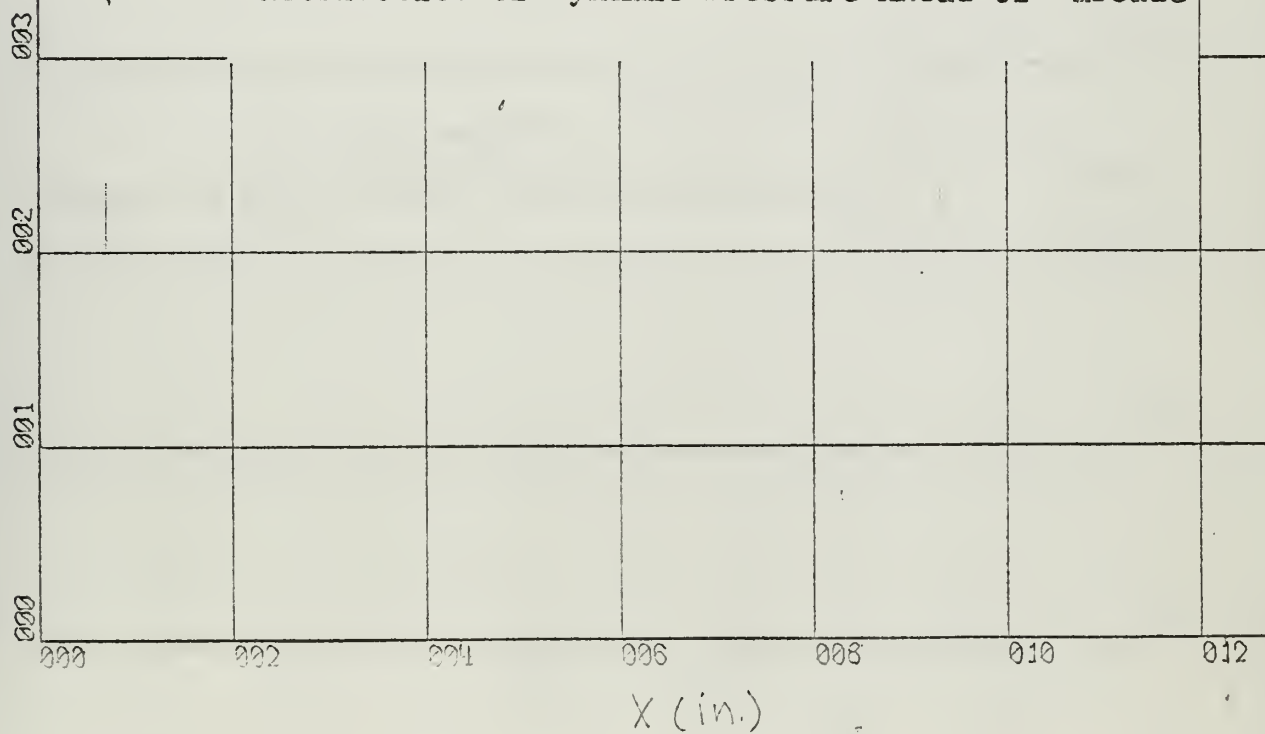


Figure C27

Distribution of Dynamic Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 1.00E+00 UNITS/INCH.

RUN 304

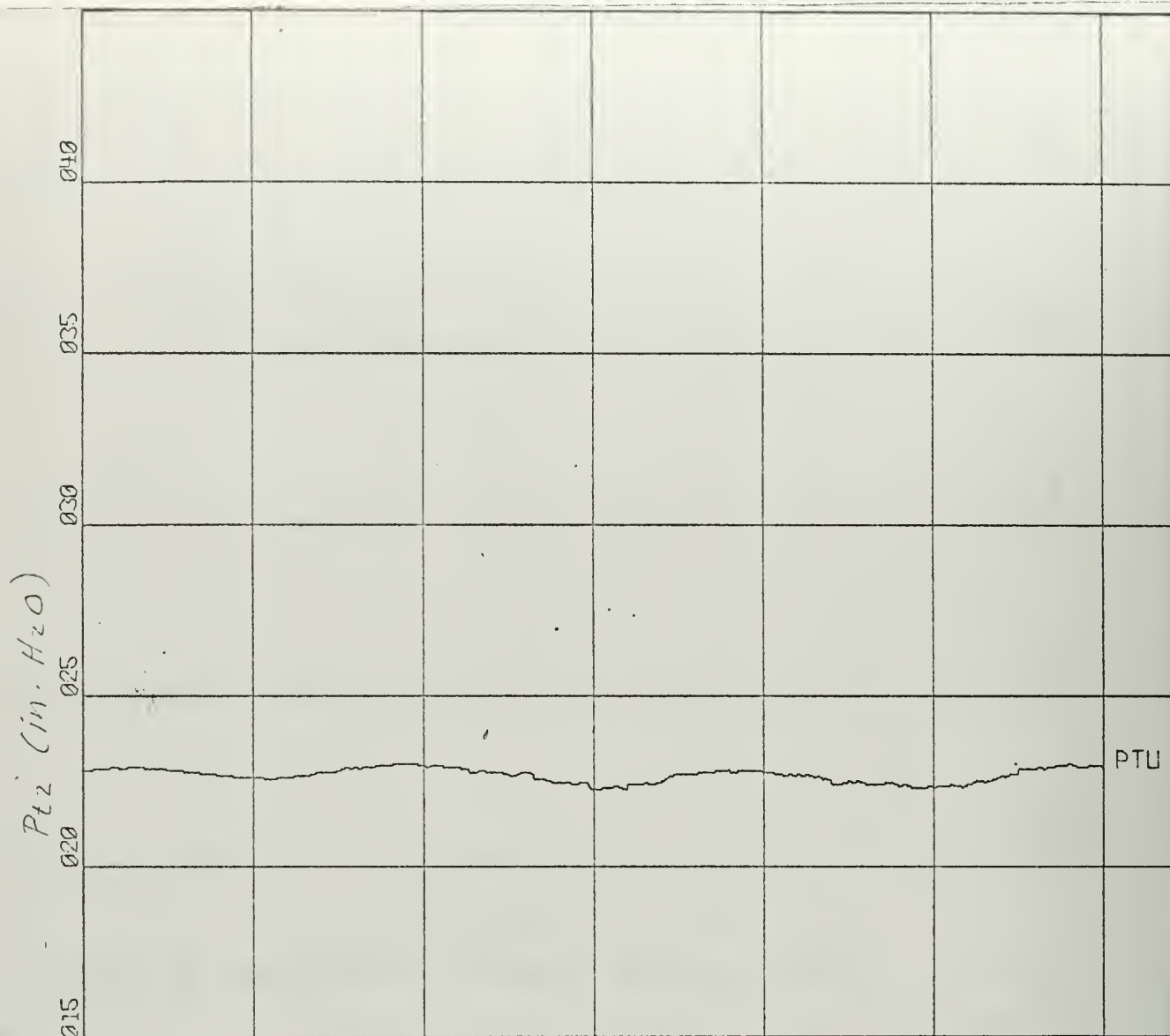
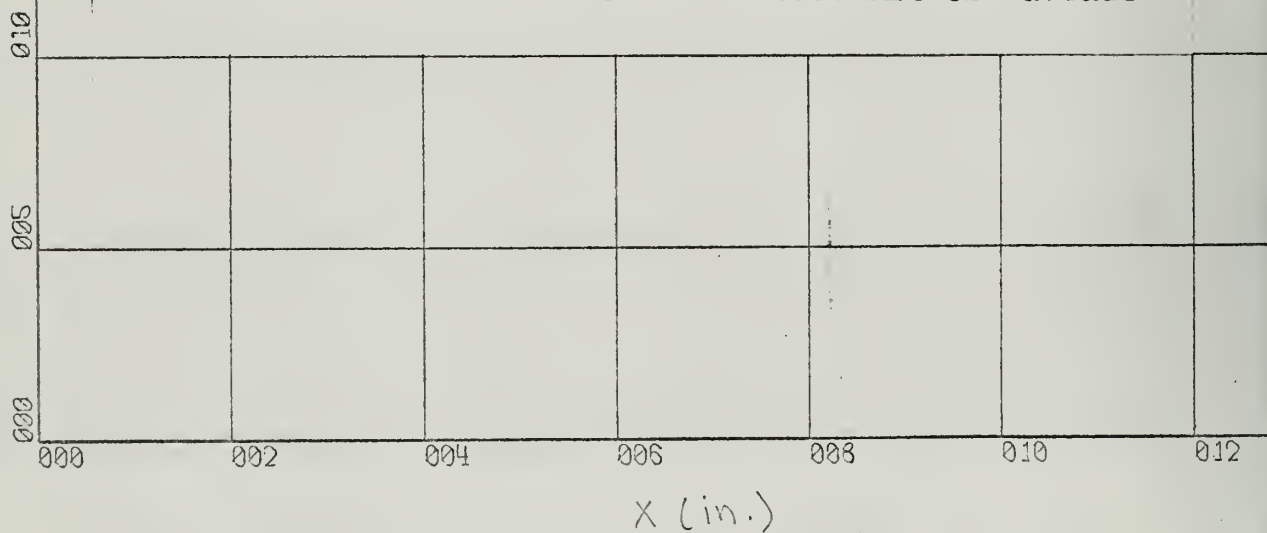


Figure C28

Distribution of Total Pressure Aft of Cascade



X-SCALE - 2.00E+00 UNITS/INCH.
Y-SCALE - 5.00E+00 UNITS/INCH.

RUN 304

ROTOR PROFILES

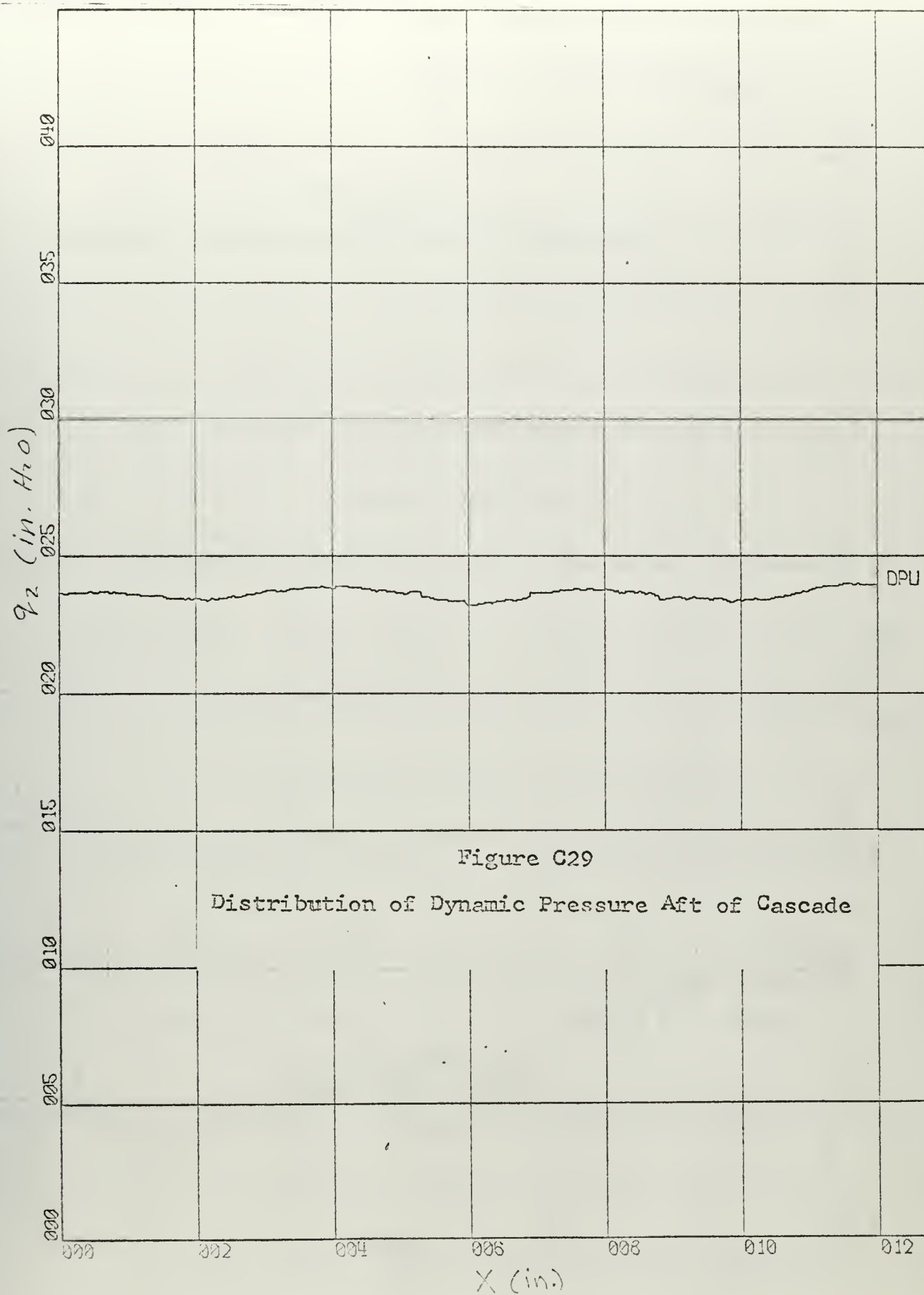


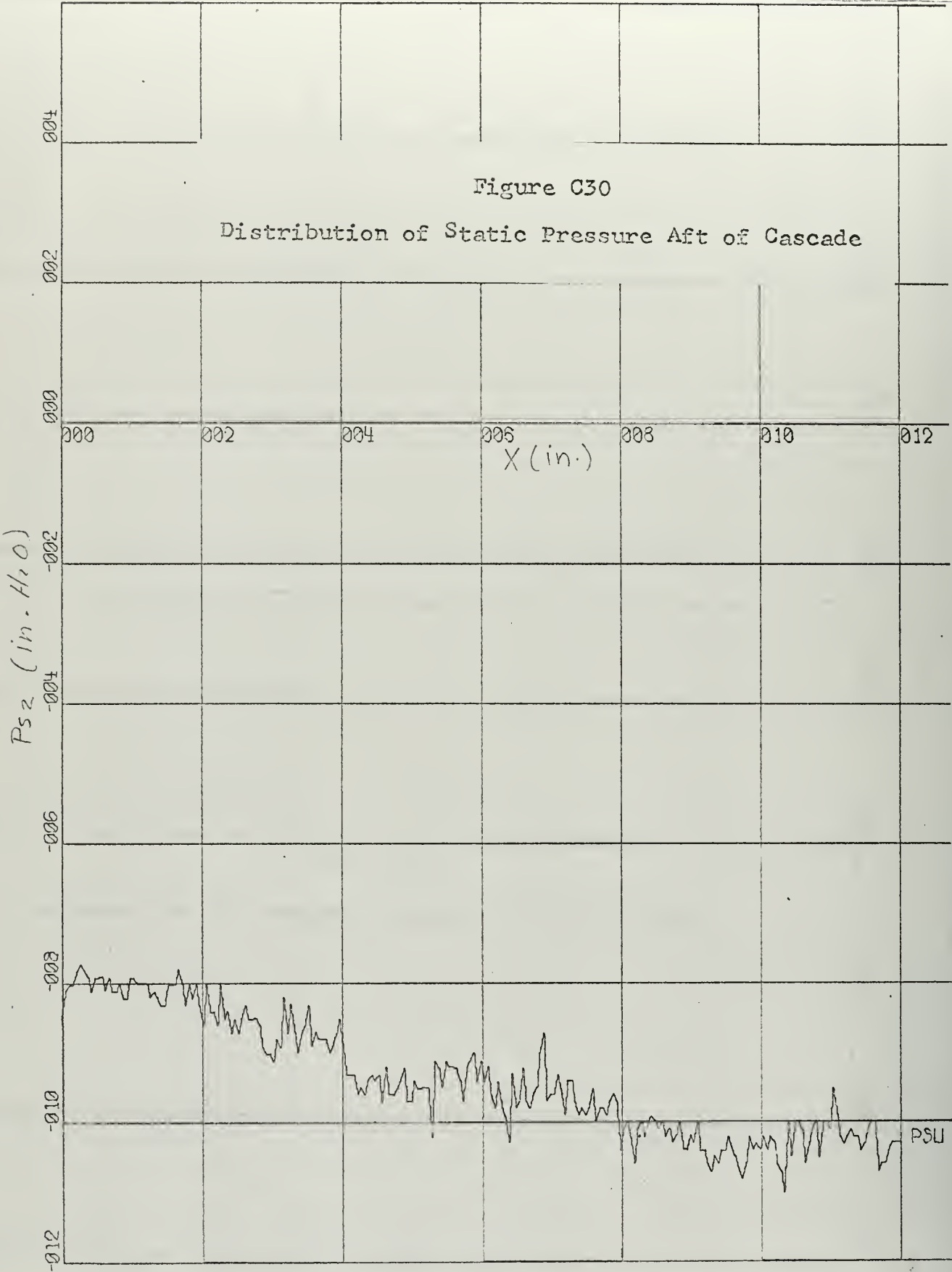
Figure C29
Distribution of Dynamic Pressure Aft of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN - 304

141 ROTOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E-01 UNITS/INCH.

RUN 304

142 ROTOR PROFILES

Table C6

PROPULSION LABORATORY
U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 305

BAROMETRIC PRESS. = 29.79 IN. HG.

PLENUM TEMP. = 71.0 DEG. F.

STAGGER ANGLE = -4.50 DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)

FAR AFT (STATION 3)

V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
168.254	56.12	2237.9	2203.3	334.858	-71.95	2222.7	2088.8

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)

UPPER TRAVERSE (STATION 2)

PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2237.9	2203.3	2222.8	2088.9

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAG
36.89	36.30	51.67	3.01

TOTAL TURNING ANGLE OF THE FLOW (DEG) = 128.07

RUN NO. = 305 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .10345

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V_0 AND V_3

CL

CD

4.4094

.2567

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CL0

CD0

2.7086

.1577

CONSTRICITION FACTOR = .9412

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00242951

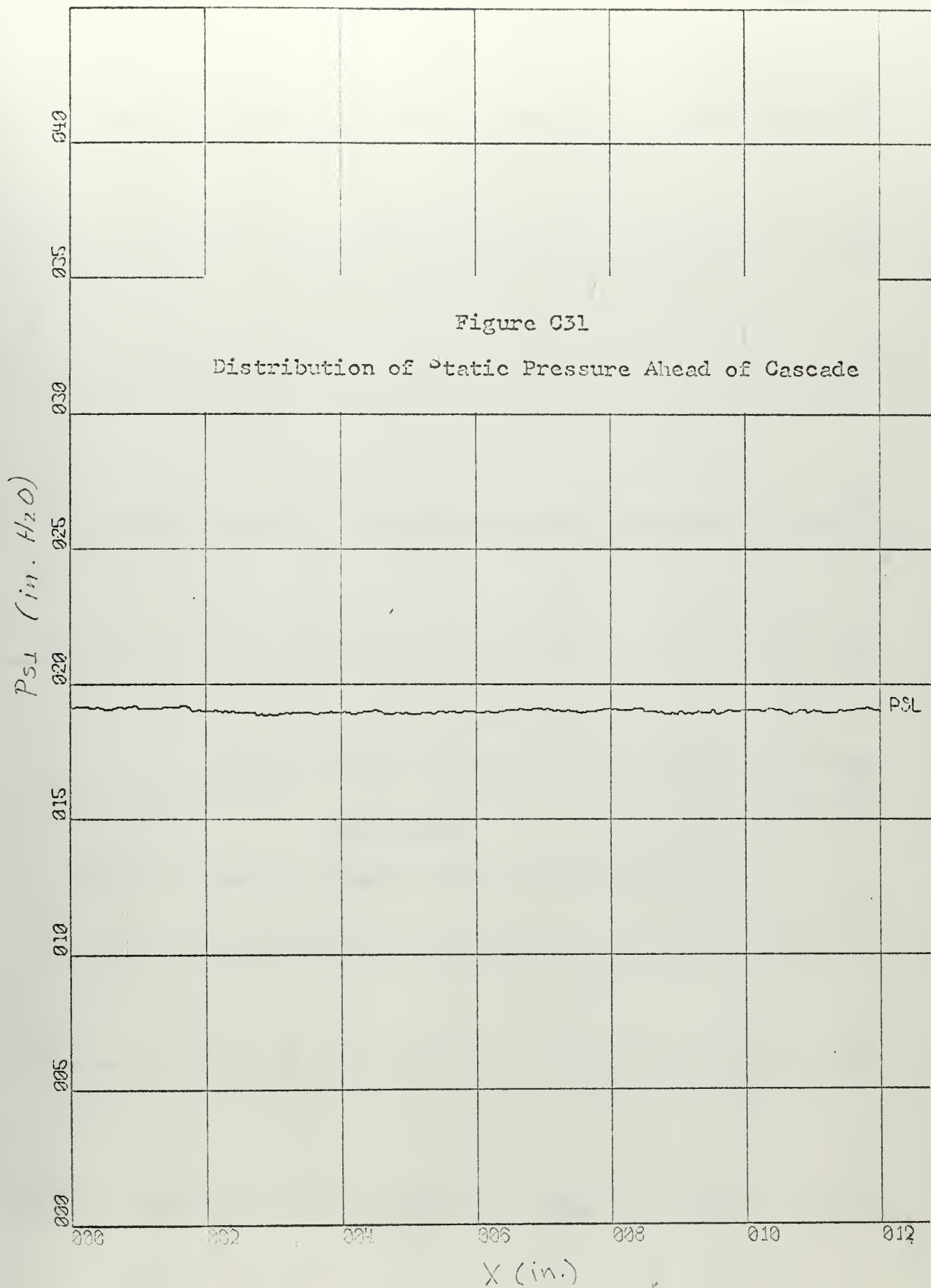
DENSITY(SLUGS PER CU.FT.) FAR AFT = .00233320

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

1124886.

.1490

TIME, 4 MINUTES AND 35 SECONDS



X-SCALE - 2.00E+00 UNITS/INCH.

Y-SCALE - 5.00E+00 UNITS/INCH.

RUN 305

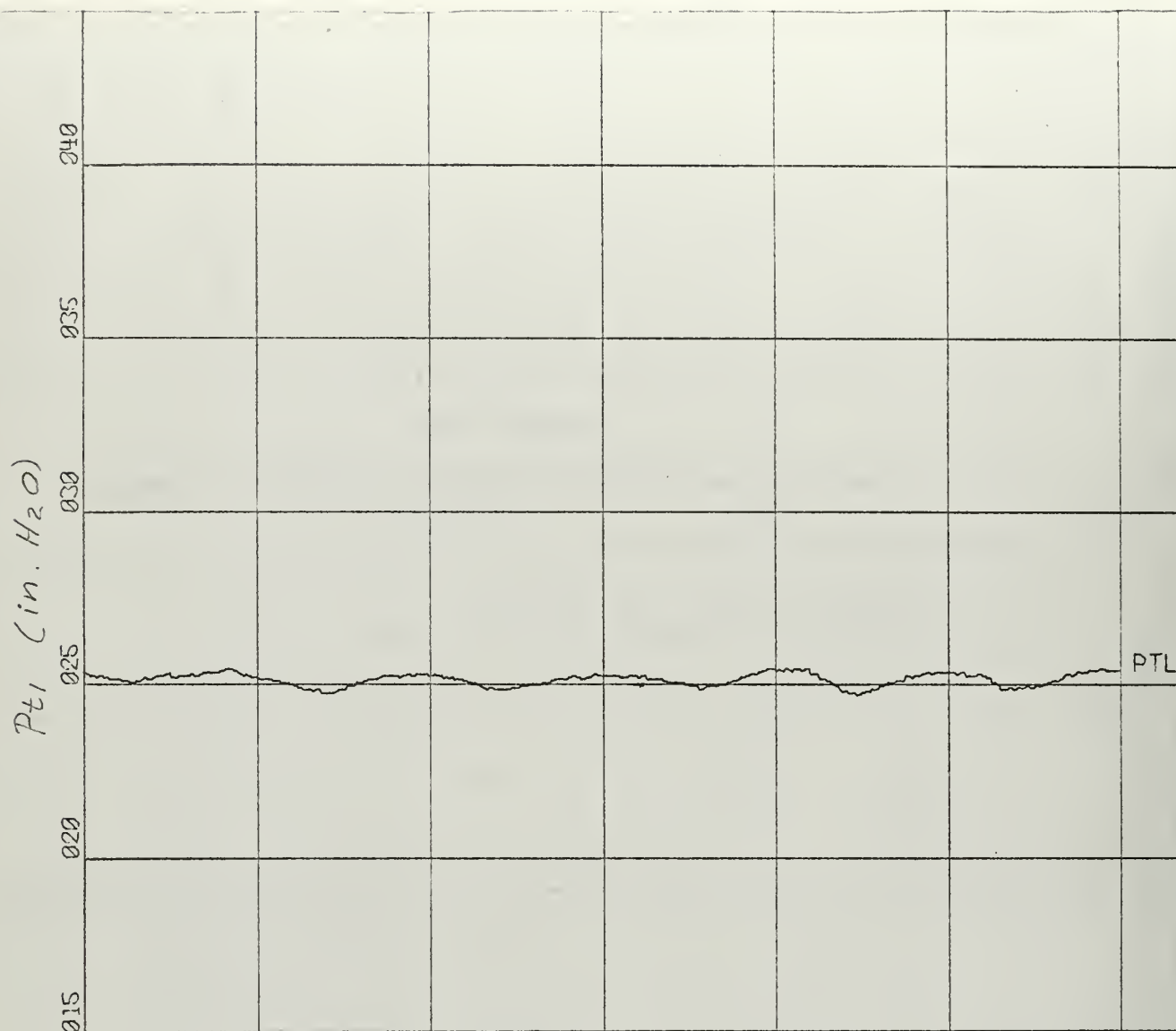
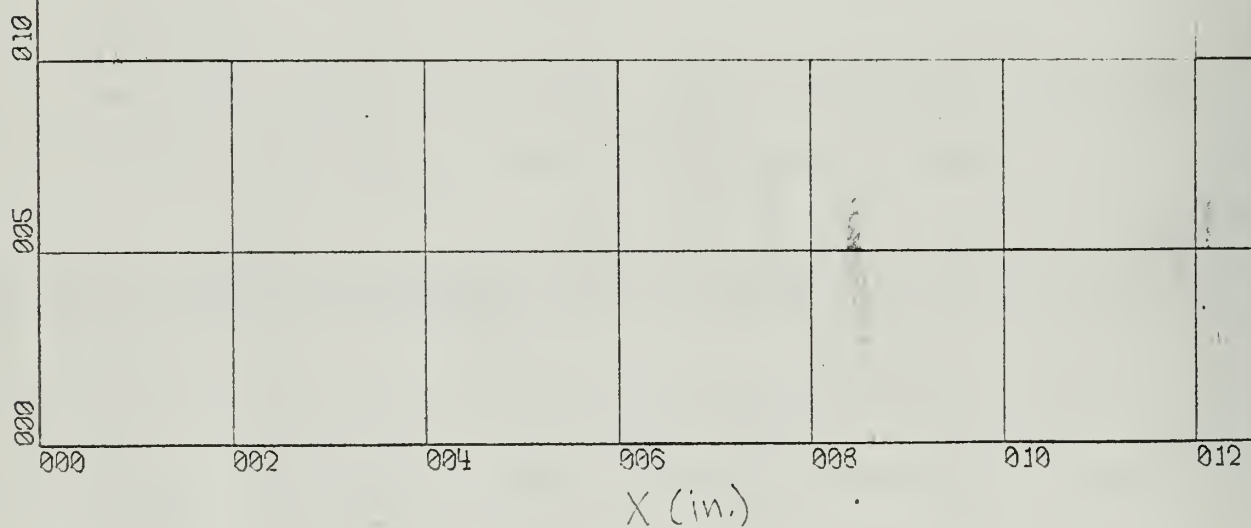


Figure C32

Distribution of Total Pressure Ahead of Cascade



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 305

ROTOR PROFILES

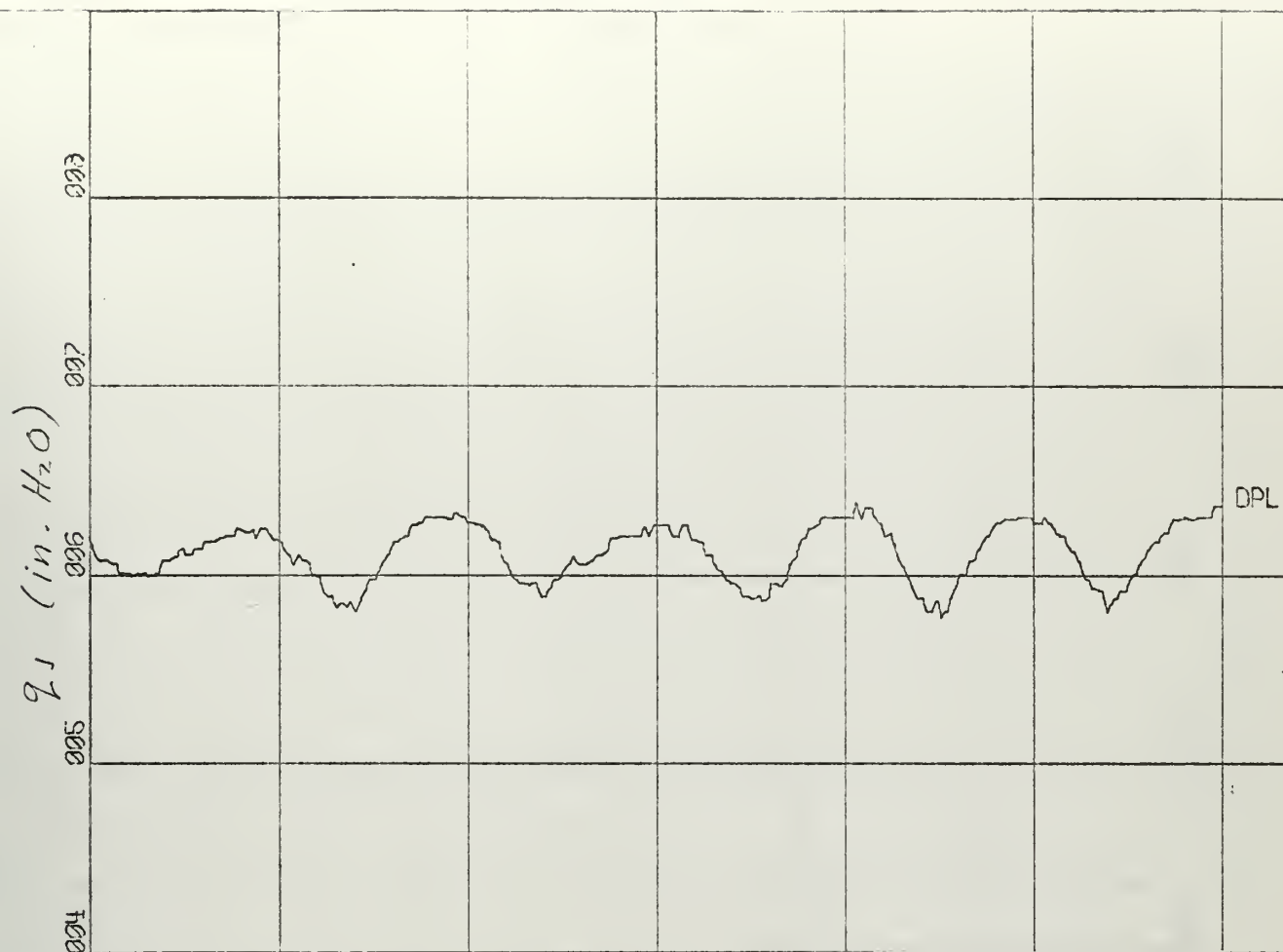
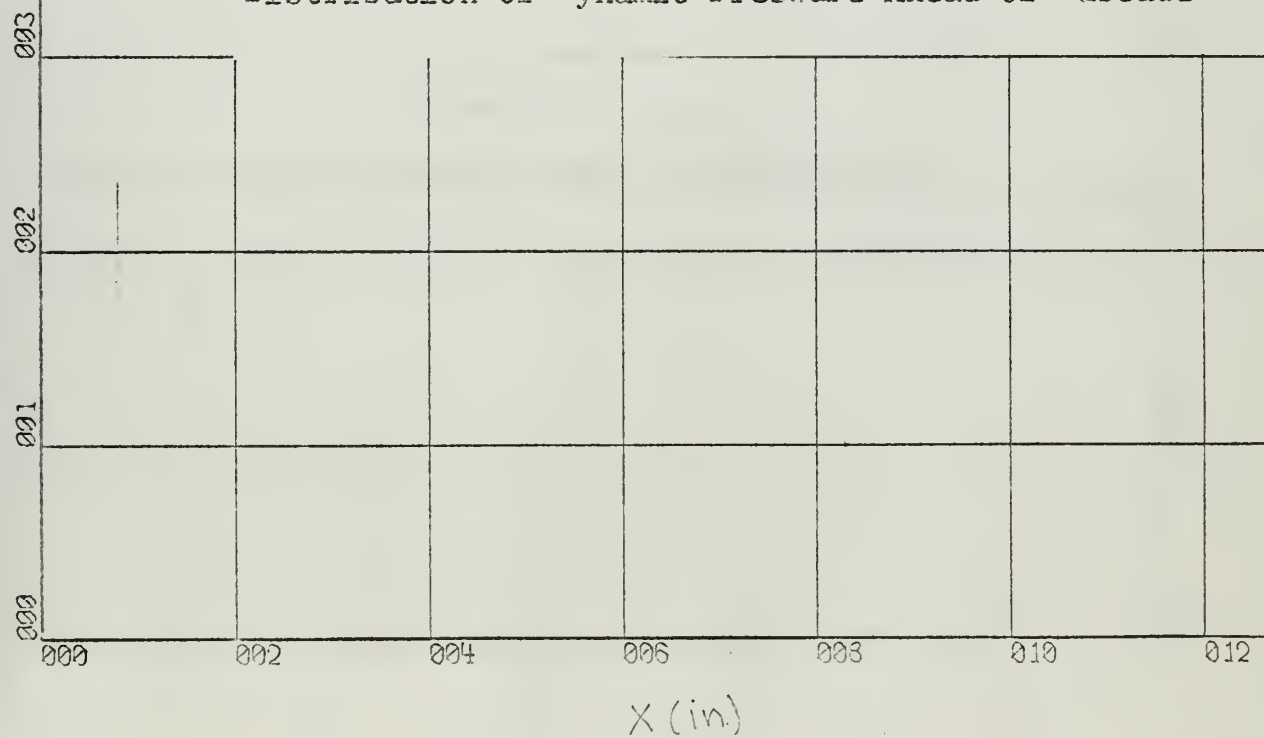


Figure C33

Distribution of Dynamic Pressure Ahead of Cascade

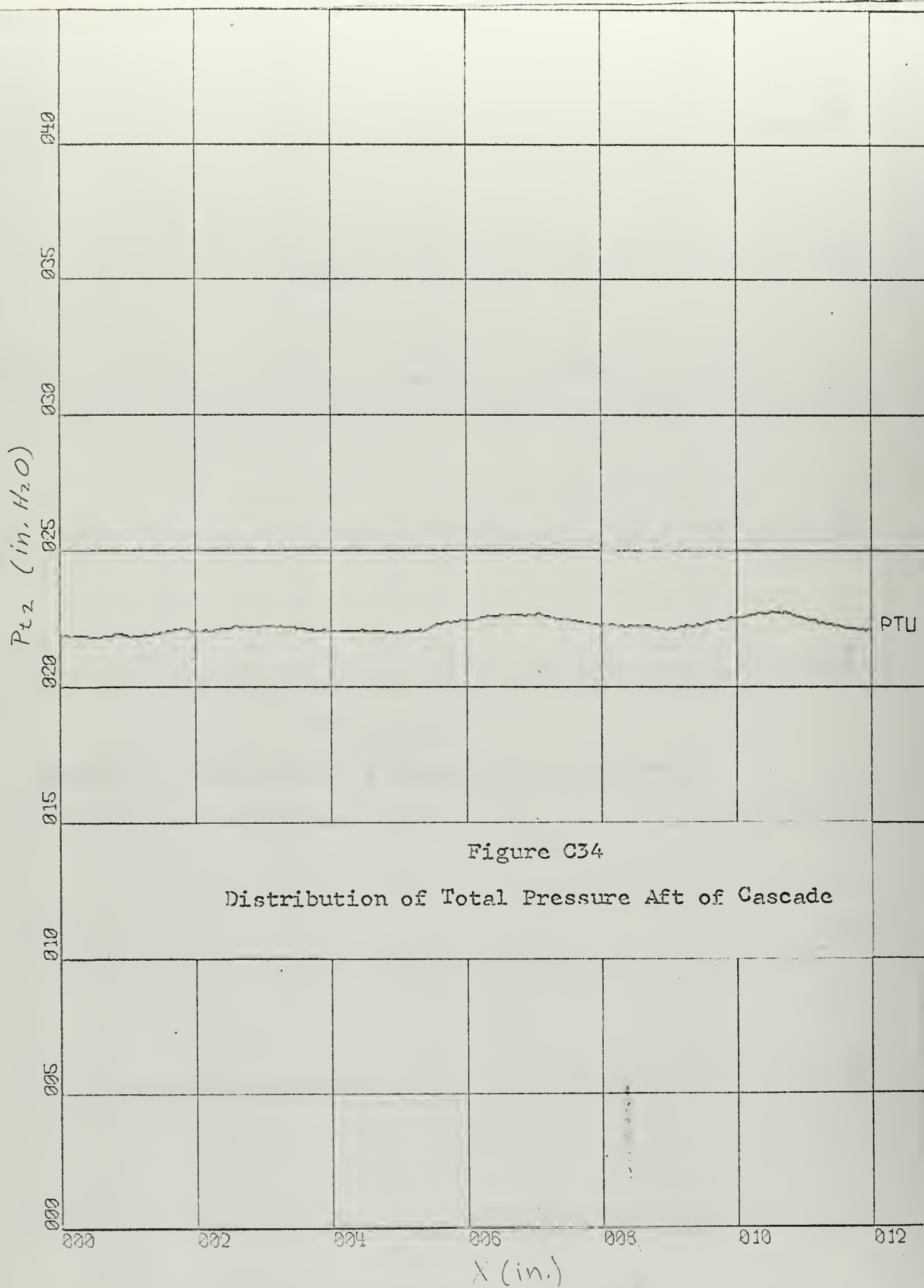


X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 1.00E+00 UNITS/INCH.

RUN 305

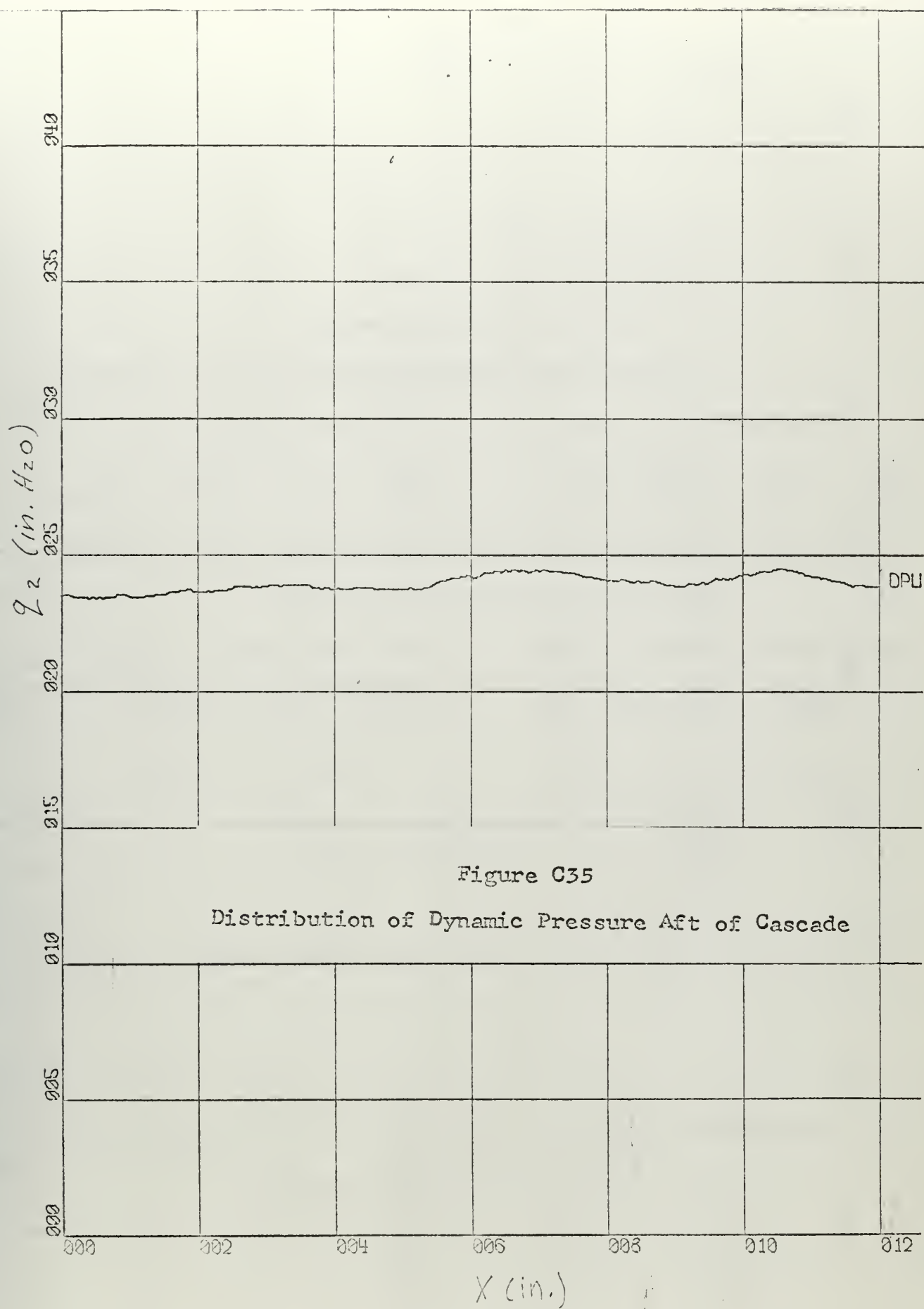
ROTOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 305

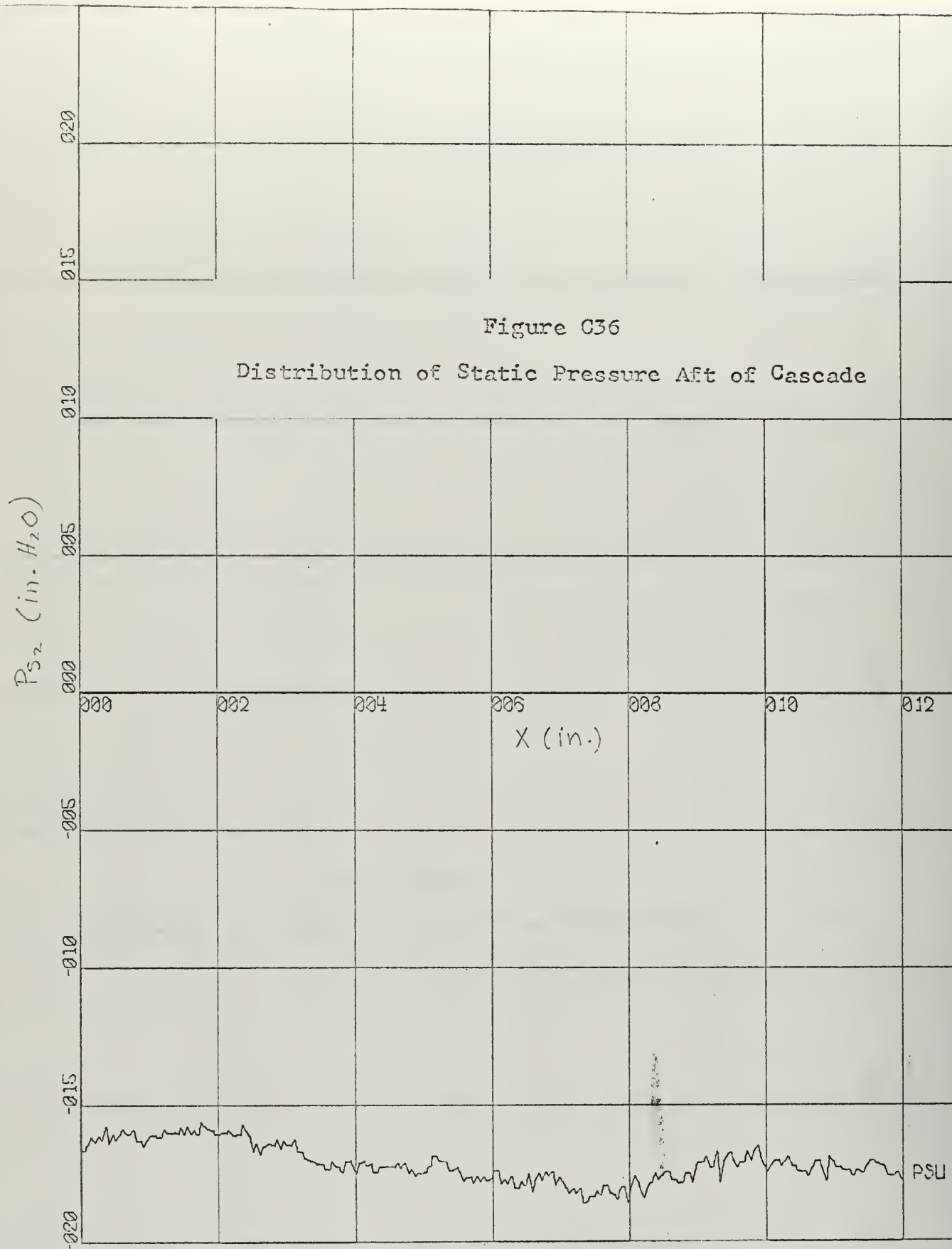


X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 305

ROTOR PROFILES



X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E-01 UNITS/INCH.

RUN 305

ROTOR PROFILES

Table C7

PROPULSION LABORATORY
U.S. NAVAL POSTGRADUATE SCHOOL

TEST RUN NO. 306

BAROMETRIC PRESS. = 30.10 IN. HG.

PLENUM TEMP. = 71.7 DEG. F.

STAGGER ANGLE = -4.50 DEG.

SOLIDITY = 1.66

BLADE PROFILE =

FAR AHEAD (STATION 0)				FAR AFT (STATION 3)			
V0 (FT/SEC)	ALPHA 0 (DEG)	PT0 (PSF)	PS0 (PSF)	V3 (FT/SEC)	ALPHA 3 (DEG)	PT3 (PSF)	PS3 (PSF)
269.861	68.62	2260.4	2171.3	337.933	-70.42	2249.2	2111.5

CONDITIONS AT THE MEASURING PLANES

LOWER TRAVERSE (STATION 1)		UPPER TRAVERSE (STATION 2)	
PT1 (PSF)	PS1 (PSF)	PT2 (PSF)	PS2 (PSF)
2260.4	2171.3	2249.3	2111.5

FORCES ON THE BLADES IN LBS. PER FT.

AXIAL	TANGENTIAL	LIFT	DRAG
17.64	48.18	51.26	2.26

TOTAL TURNING ANGLE OF THE FLOW (DEG) = 139.03

RUN NO. = 306 CONCLUDED

LOSS COEFFICIENT , MIXING LOSS INCLUDED = .07393

LIFT AND DRAG COEFFICIENTS BASED ON
THE VECTORIAL MEAN OF V_0 AND V_3

CL

CD

6.2910

.2772

LIFT AND DRAG COEFFICIENTS BASED ON
CONDITIONS FAR AHEAD OF THE CASCADE

CLO

CDO

1.0538

.0464

CONSTRICTION FACTOR = .8878

DELTA X LOWER = 12.00

DELTA X UPPER = 12.00

DENSITY(SLUGS PER CU.FT.) FAR AHEAD = .00240804

DENSITY(SLUGS PER CU.FT.) FAR AFT = .00235620

REYNOLDS NUMBER(CHORD) AND MACH NUMBER
REY MO

TIME, 4 MINUTES AND 1145262. SECONDS .2388

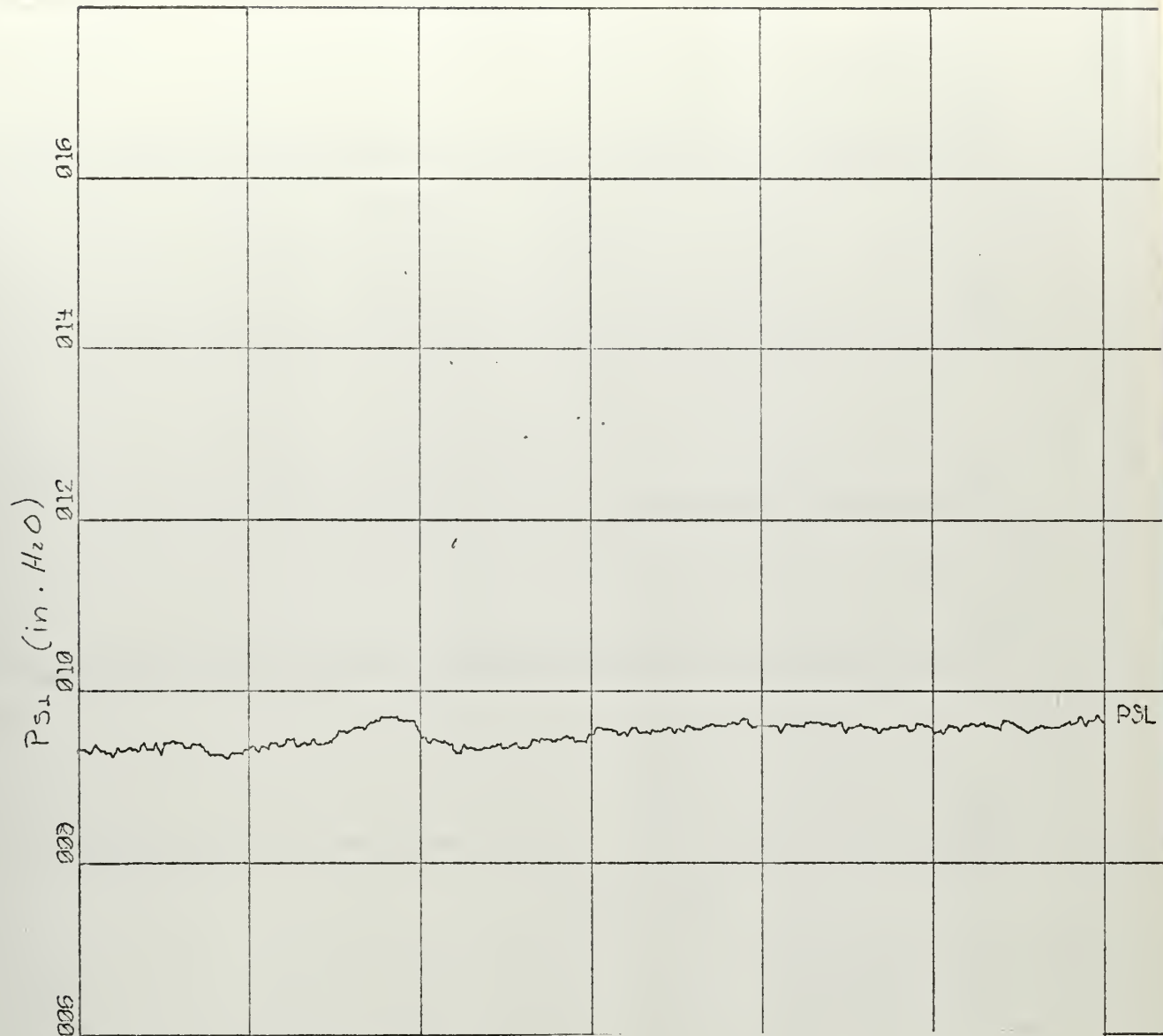
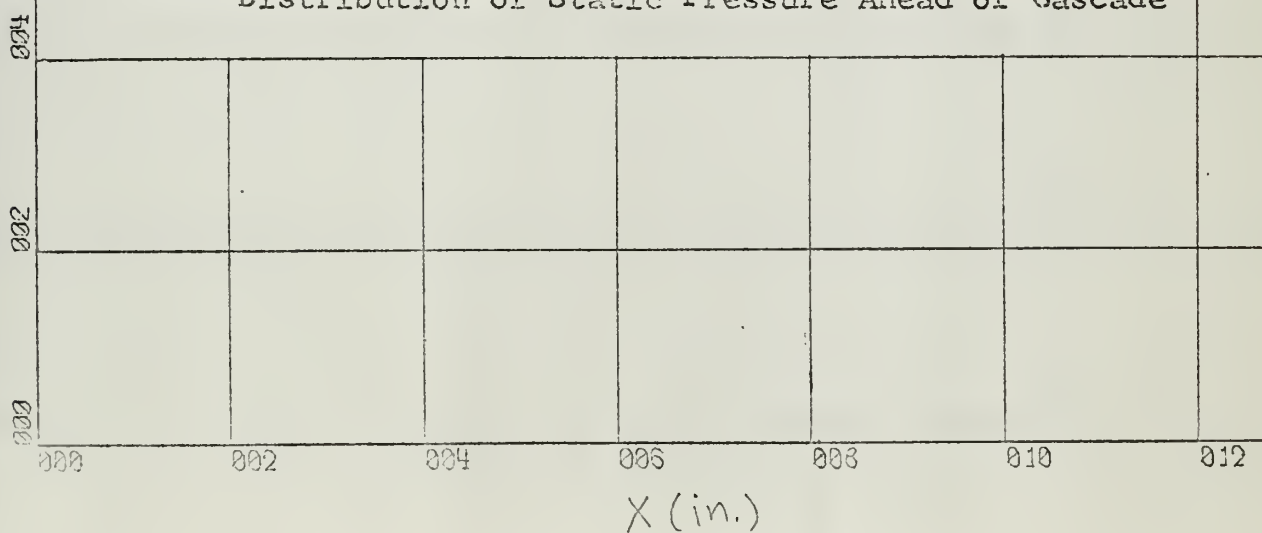


Figure C37

Distribution of Static Pressure Ahead of Cascade



X-SCALE - 2.00E+00 UNITS/INCH.

Y-SCALE - 2.00E+00 UNITS/INCH.

RUN 306

153

ROTOR PROFILES

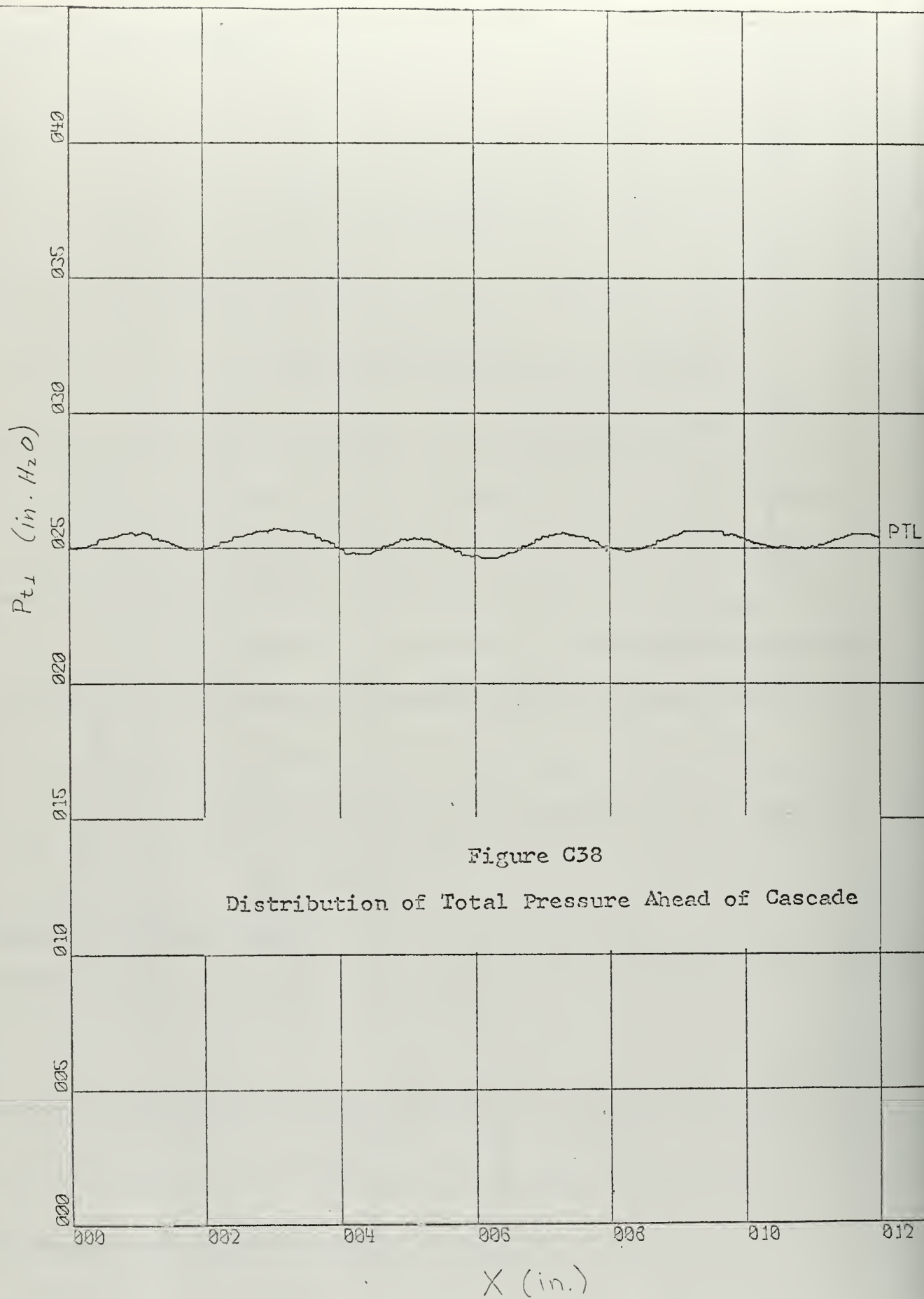


Figure C38

Distribution of Total Pressure Ahead of Cascade

X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 5.00E+00 UNITS/INCH.

RUN 306

ROTOR PROFILES

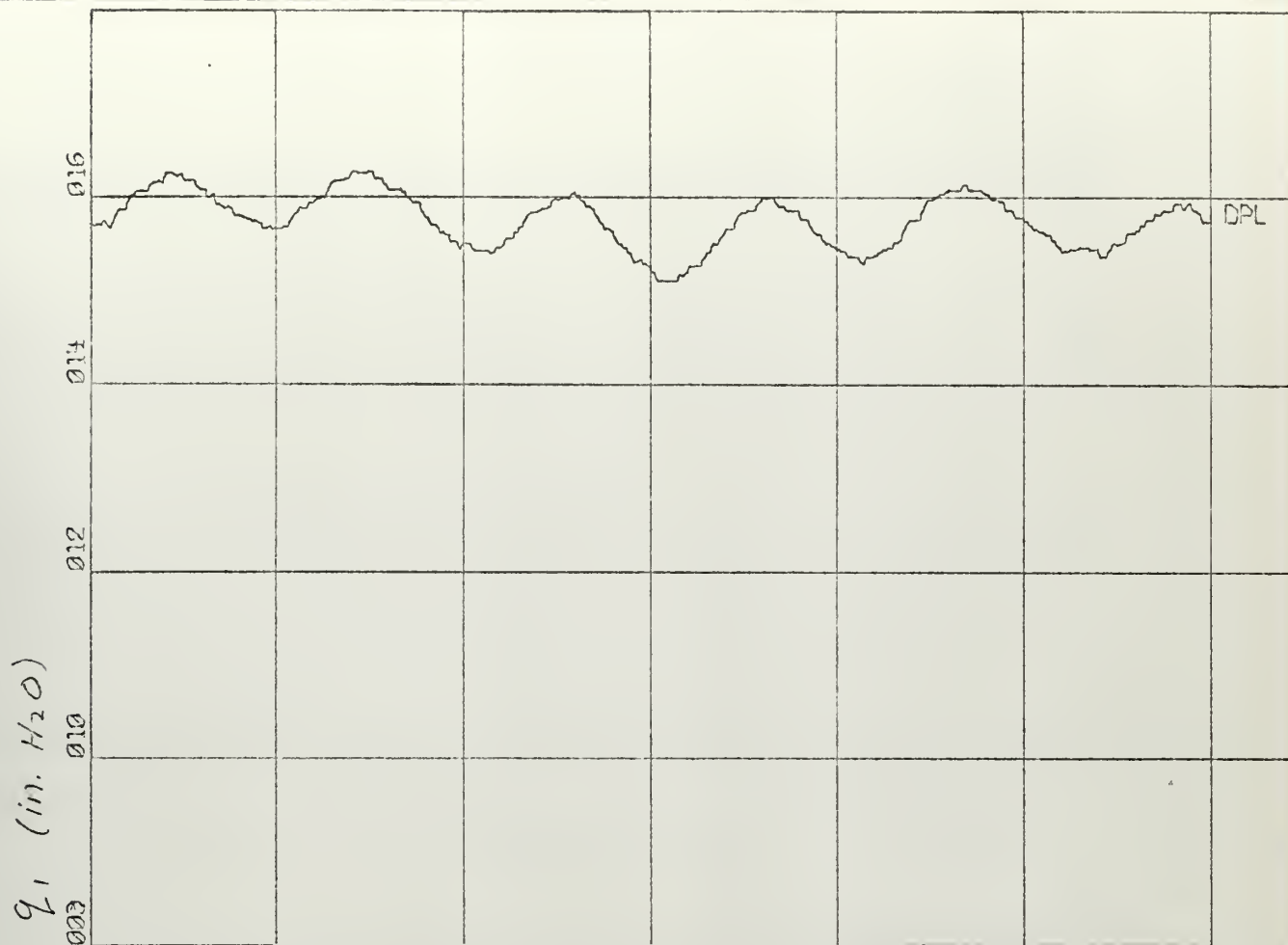
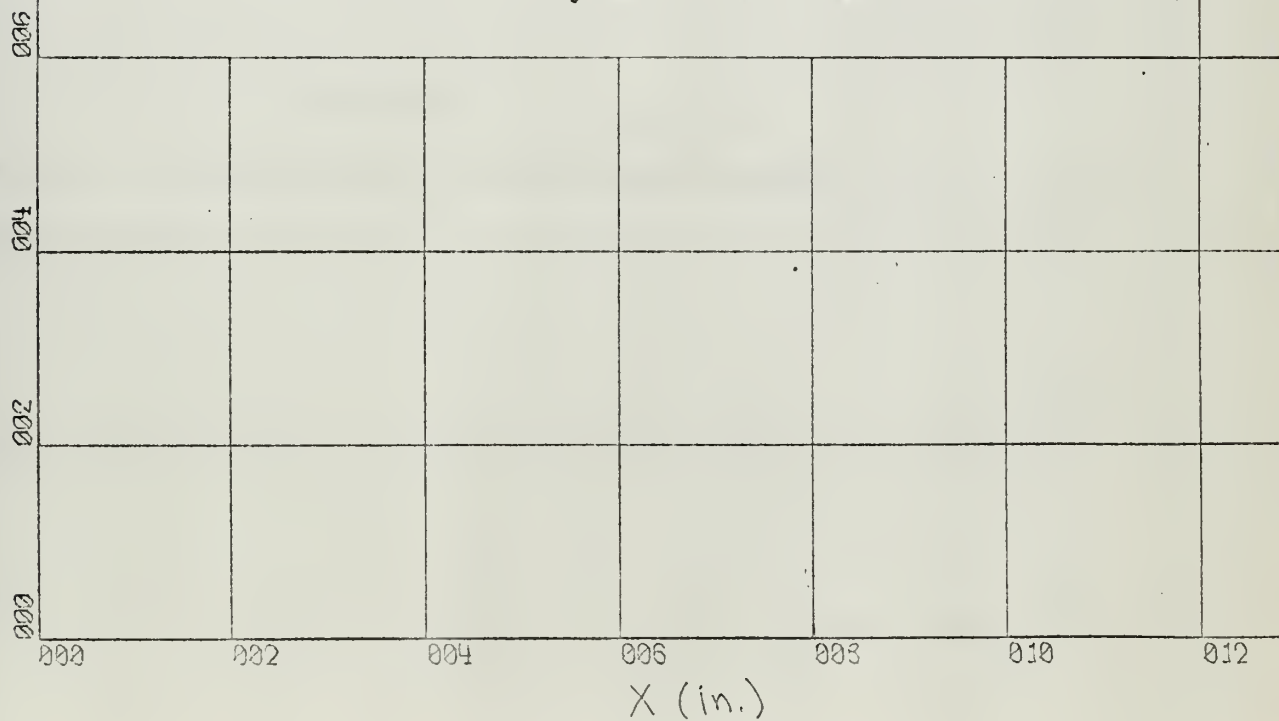


Figure C39

Distribution of Dynamic Pressure Ahead of Cascade



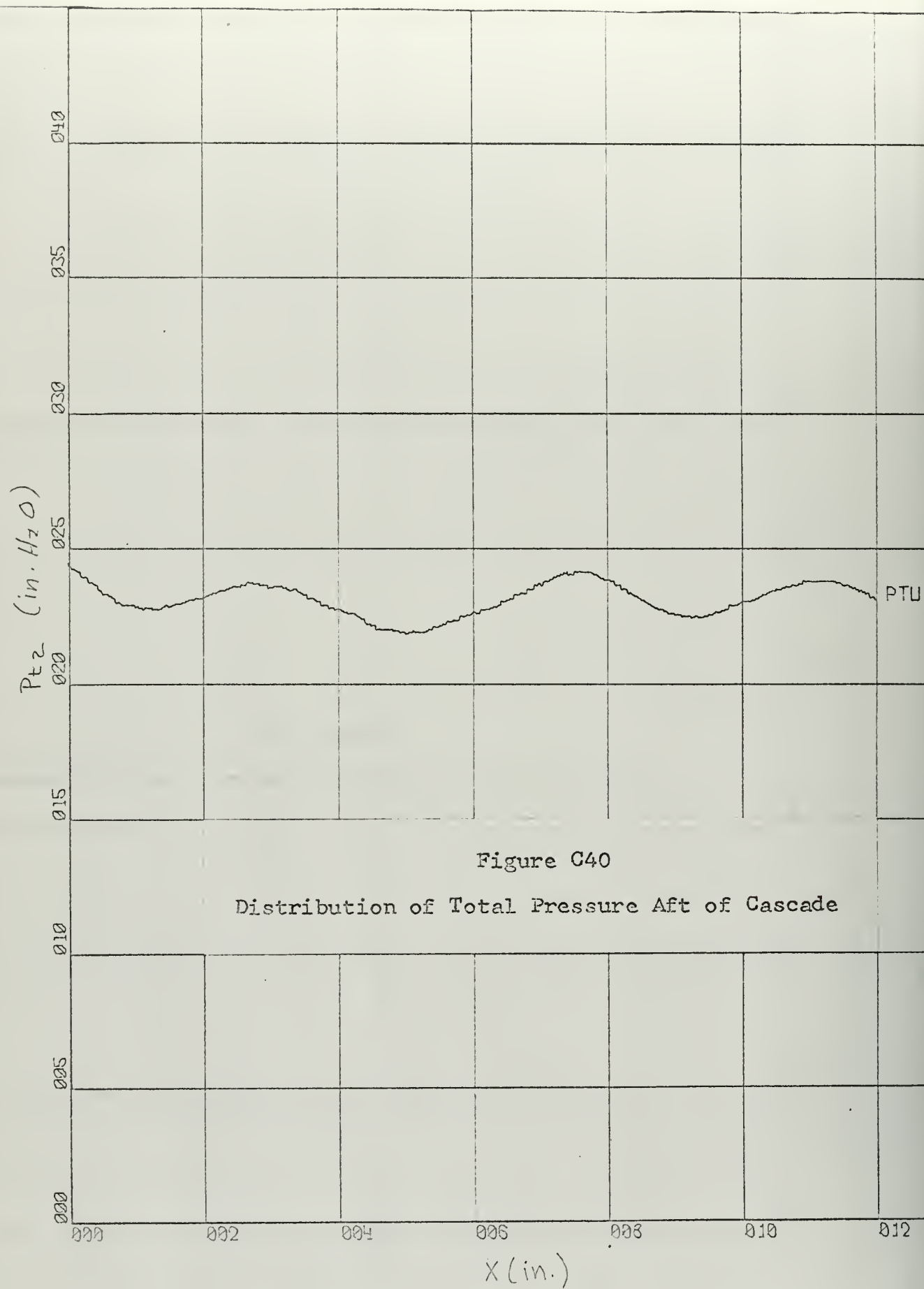
X-SCALE = 2.00E+00 UNITS/INCH.

Y-SCALE = 2.00E+00 UNITS/INCH.

RUN 306

155

ROTOR PROFILES

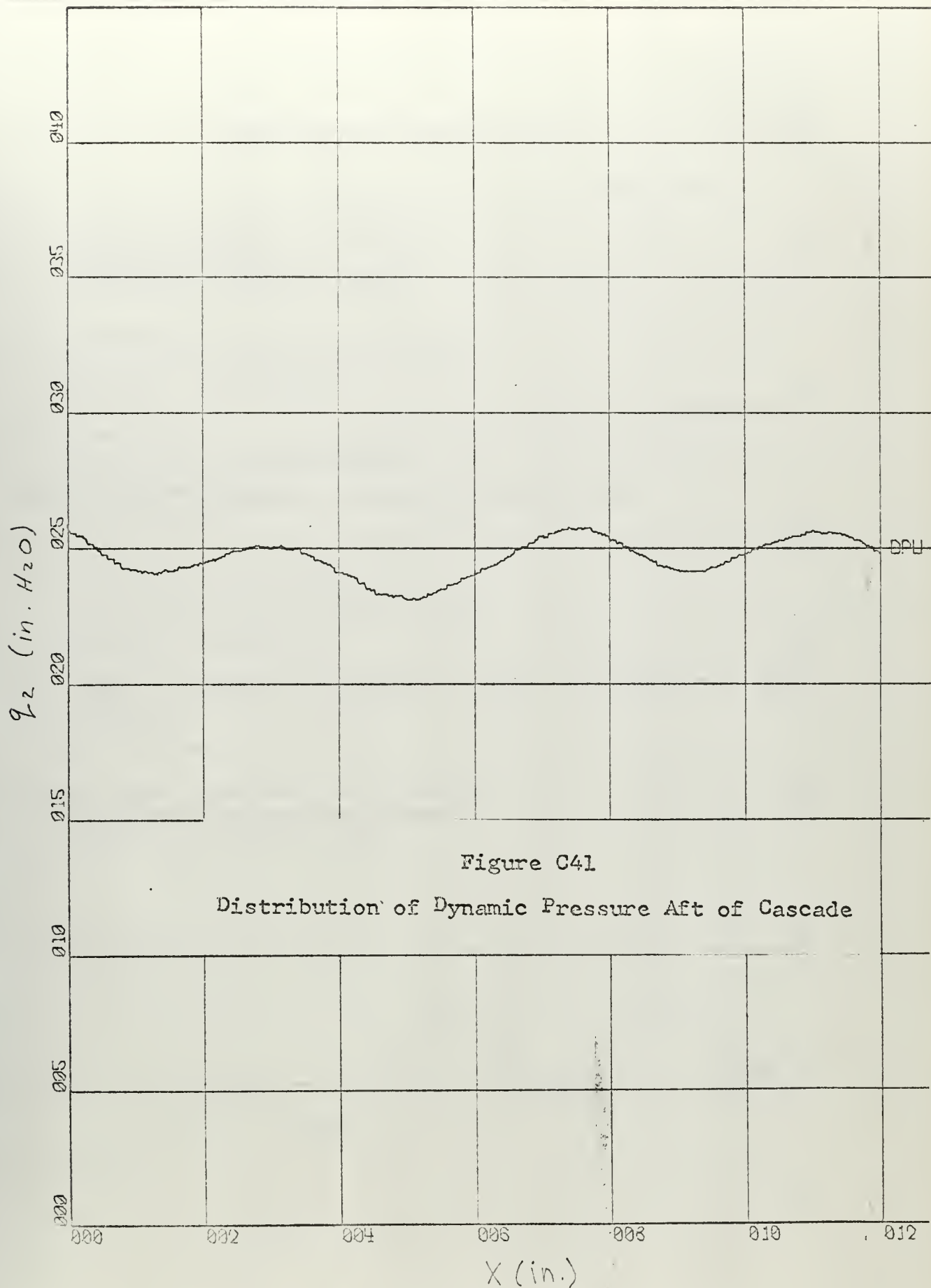


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Figure C42

Distribution of Static Pressure Aft of Cascade

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1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION	
U. S. Naval Postgraduate School		UNCLASSIFIED	
		2b. GROUP	
		N/A	
3. REPORT TITLE Cascade Tests of the Blading of a High-Deflection, Single-Stage, Axial-Flow Impulse Turbine and Comparison of Results with Actual Performance			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
Thesis			
5. AUTHOR(S) (Last name, first name, initial)			
BARTOCCI, John E.			
6. REPORT DATE		7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1966		159 103	12
8a. CONTRACT OR GRANT NO.		9a. ORIGINATOR'S REPORT NUMBER(S)	
N/A		N/A	
b. PROJECT NO.			
N/A			
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
N/A		N/A	
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N/A		Commander, Naval Air Systems Command, Navy Department, Washington, D. C.	
13. ABSTRACT			
<p>Cascade tests were performed on models of the stator (nozzles) and rotor blade rows of a high deflection, single-stage, axial-flow impulse turbine. The tests were performed at the Rectilinear Cascade Test Facility of the Propulsion Laboratories, United States Naval Postgraduate School. The results of these tests were compared with the performance data of the actual turbine. The comparison showed that profile and mixing losses, through not negligible, constitute only a small percentage of the overall rotor loss. Also, the inlet flow angle at which the minimum loss occurred for the Cascade flow was significantly different from the inlet flow angle at which minimum actual rotor loss occurred.</p>			

14. KEY WORDS	LINK A		LINK B		LINK C	
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